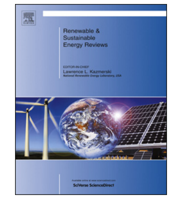
Renewable and Sustainable Energy Reviews 27 (2013) 692–708

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



An overview on doubly fed induction generators′ controls and contributions to wind based electricity generation

Abdullah Asuhaimi B. Mohd Zin [a], Mahmoud Pesaran H.A. [a,*], Azhar B. Khairuddin [a], Leila Jahanshaloo [b], Omid Shariati [a]

[a] Department of Electrical Power Engineering, Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor, Malaysia
[b] Department of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor, Malaysia

ARTICLE INFO

Article history:
Received 4 December 2012
Received in revised form
3 July 2013
Accepted 5 July 2013
Available online 8 August 2013

Keywords:
Renewable energy
Doubly fed induction generator
Wind energy
Energy conversion

ABSTRACT

Undoubtedly, energy has a significant role in economic growth and technical developments. Renewable energy resources are becoming more important in recent years due to their tremendous contributions to the independence of power generation industry from traditional fossil energy resources. Wind energy has been outstanding among renewable energy resources since continuous harvestable potential on the earth is approximately around 10^6 MW. Concerning the variable nature of wind energy, the variable speed machines, especially doubly fed induction generators (DFIG) are one of the considerations for wind energy conversion systems (WECS). Their implementation in renewable energy conversion systems is dramatically increasing due to their numerous advantages such as low cost and small size, the elimination of external DC source, the ability to produce maximum power under various wind and rotational speeds, the capability of controlling active and reactive power, and the opportunity to employ cheaper and smaller convertors and controllers. This paper is an extensive review of researches in the past 30 years on DFIG. The study starts with describing general perspective on wind energy and commonly used generators in wind conversion. Then it presents more details on DFIGs operational modes, utilizations, their modeling and simulation. It is followed by DFIG control methods and overviews of different employed electrical and mechanical controlling methods. Finally the review on the mutual impact of DFIG on power networks and vice versa, including wind uncertainty, power and frequency stability, power and voltage quality, operation under steady state, dynamic and fault conditions, and protections is given. Based on the review DFIG has advantages in terms of electrical, mechanical, and economic perspectives. It can be concluded that the DFIG has the most promising future for WECSs in power generation to complement the conventional systems.

Contents

* Corresponding author. Tel.: +60 12 3712537.
E-mail addresses: abdullah@fke.utm.my (A.A.B. Mohd Zin), mpesaran@fkegraduate.utm.my (M. Pesaran H.A.), azhar@fke.utm.my (A.B. Khairuddin).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.07.010

1. Introduction

Up to the present, the majority of electricity have been generated from conventional fossil sources, which are mostly non-renewable sources such as gas, oil and coal. This kind of energy conversion emits a large amount of carbon dioxide to the atmosphere, which results in global warming. For this reason and also due to rapid development of modern electricity production technologies, old fuel burner power generation units are being replaced with new available technologies. Among these recent electricity generation technologies, the renewable energy convertors are magnificently shining with respect to their smaller size, lower cost per unit and being more environmental friendly [1–5]. On the other hand, concerns about fuel source's limitations and the unstable price of thermal plants generated electricity per kW associated with fluctuating price of fuel cause a global trend to replace limited energy sources with abundant alternatives. Wind energy as a plentiful renewable-energy source is dominating this area in comparison with its opponents such as photovoltaic or micro hydro turbines [6–9].

Considering the latest technologies, wind energy generators have remarkably improved. These advances caused a noticeable rise in wind turbines presence among generation technologies in recent years. According to the Wind Global Energy Council (WGEC) 2010 annual report, wind energy is being developed and used in more than 70 countries [10]. Global wind energy utilization annual growth rate was 24.6% in 2009. However, this value dropped by 0.5% in 2010 because of financial crisis, the plunge could be more tragic if China had not been introduced as a new forerunner to the field of wind energy. While US installed 50% less in 2010 compared with 2009 and the Europe market was down by 7.5%, China owned almost half of the worldwide installation, with the amount of 18.9 GW. This huge installation preserved the global increase rate at 24.1% and yielded 195 GW of new wind convertor integration in total, which was almost twice of 94.19 GW that was installed in the late 2007 [11,12].

There were several types of generators, which have been used as wind energy convertors. The most common type of generator in the old days was synchronous generators while these days by manufacturing technology improvements, induction generators of different kinds become more accepted in wind energy conversion field [13,14]. Induction generators, especially doubly fed induction generators are becoming more and more popular in renewable source employment [15–17]. Simple induction generators have some weaknesses such as reactive power consumption and unregulated voltage profile during variable rotor speed. These problems could be solved by implementation of DFIG and power electronic convertor or regulators [18–20]. This paper is an overview and conclusion on the last 30 years research, which have been done related to DFIG controllers, their impact on power networks and vice versa.

2. Wind energy overview

Renewable resources are abundant, and they are easily accessible all over the world. During the last century, hydro units have been matured in electricity generation, and today approximately one-fifths of worldwide electricity demand is being supplied by hydro powers. Meanwhile, in the most developed countries the economically reasonable opportunities of constructing new and large hydro electricity projects have already been exploited [3]. Consequently, other renewable resources should fill the vacant space of hydro electricity to fulfill the expected economy. The

increase in renewable energy sources usage could make energy market independent of fuel price fluctuations. Otherwise, regarding the continuous increase in electricity request worldwide, the cost of energy resources will rise, the economic burden of oil use will grow, and finally the probability of fossil fuel supply disruption will increase. Switching to renewable resources besides economic profits could bring other benefits such as clean environment and less global warming by reducing green house gas emission [3,4,21,22].

Modern wind turbines availability is normally more than 98% and in a proper windy area they can perform with capacity factors of 35–40%. Additionally, over the last 20 years the cost of wind based electricity has descended about 90%. Consequently, a new large wind farm which is constructed at a windy site can produce electricity at a cost of 4–6 ¢/kWh (in U.S. dollars). This brings the cost of wind generated electricity in the range of generated electricity from new conventional power plants. These improvements open new horizons to the more secure and reliable future of wind energy while offering better quality for life in a less pollution environment [23].

Wind energy is the fastest growing energy source in the world. This renewable and neat source has always been available and had a background for more than 3000 years old, while it has been employed for electricity generation about 120 years ago [24,25]. In spite of forward trend of development in wind employment technology, oil price fluctuation always had a significant impact on wind generators′ development. Wind technology presence in electricity generation field has been highlighted for the first time during the 1970s oil crisis [26,27]. The global trend toward clean energy is a motivation for more integration of wind based electricity in power systems [27]. Large and small wind turbines produce electricity for networks and utilities while they support stand-alone remote areas as well [28].

2.1. Historical background

The usage of wind energy has a long history, about 3000 years ago Persians and Egyptians started using this energy for pumping water even before coal and refined oil were discovered. Furthermore, they add wind mills besides water wheels to grind wheat and rice, centuries prior to the Europeans [29]. Probably, the first wind generator was built in Scotland by Professor James Blyth in 1887 [30]. On the following year in 1888, the preliminary operational wind machine was developed by Bruch and his colleagues and installed on the Atlantic coast. The diameter of that turbine was 17 m and it was equipped with 144 cedar blades. It generated only 12 kW which was used to charge batteries as DC supply for lamps and motors [31]. Subsequently, real development of wind energy as an electricity source began, and it moved forward step by step [32]. Vantikanten blades were applied by Kurt Bilau in 1920 to design a modern windmill [33]. During 1920–1930s, the windmill popularity rose and reached its highest peak by the end of this period with more than 600,000 wind turbine units installed in farms and rural areas in the United States. Most of those wind machines were only able to produce less than 1 kW of electricity [34]. Wind market started to slow down by the end of 1950 by the development in power lines construction technology, but before that, most of the farms were using wind generated electricity by means of the latest available technology of horizontal axis wind turbine, which was built in 1941 [35]. By focusing on the wind power market it clearly could be stated that this market and the history of wind energy development are undeniably linked with fossil fuel price [36]. Wind energy employment experienced a considerable rise during the last decade. World wind energy generation doubles in every 3.5 years since the beginning of the 21st century [37,38].

Wind turbine can be categorized respecting to their design, construction, installation type or location, such as: (1) horizontal or vertical alignment, (2) using lift or drag force as motion power, (3) upwind or downwind design and utilization, (4) having one, two, three or multi blade, (5) employing pitch or stall controller for mechanical system, (6) onshore or offshore installation [39–43].

2.2. Economical analysis

Wind energy is and would be an important source of energy and therefore, the assessment of its technical, economical, and reliability impacts is crucial for energy supply future [44,45]. However, one of the most highlighted economical benefit of wind energy is reducing the energy market exposure to the fuel price fluctuations[46], but the energy generation faces uncertainties for different reasons such as economic crisis, environmental variations, resource availability, various tax structures, market regulations, wind turbines lifetime, and electricity network changes. Hence, a general assessment of electricity production cost, economic analysis accuracy, and wind energy economic perspective is still hugely uncertain and hard to get confidently predicted [23,26,47,48], and in spite of new regulation in wind energy field the electricity generation companies are still involved with basic economic and reliability issues [44].

Due to wind turbine fast developing market, its technology has also shown significant improvements. While from 1990 to 2000 the worldwide capacity of grid connected wind energy has approximately doubled every three years, the cost of wind turbine descended about 20% every time the manufactured wind turbines capacity was doubled. Nevertheless, in 2000; the Danish Energy Agency also predicted that wind turbine costs will be reduced 50% by 2020, the other researchers emphasized that the cost reduction potential is limited and this makes estimations unreliable [26]. Wind turbine price, grid connection expenses and labor payments are the three major influential parameters which form approximately 80% of wind energy total cost and O&M expenditures cover another 10%. The onshore wind cost is mainly influenced by capacity factor and wind turbine cost while for the offshore wind the distance from shore, water depth, and grid constriction and connection play the main role in accounting. The cost of wind energy has risen by 20% from 2006 to 2009 because of the increase in wind energy request together with raise in key raw material price. In 2009 the cost for onshore generated wind electricity was between 4.5 and 8.7 €¢/kWh and the price for offshore was from 6 to 11.1 €¢/kWh [48]. At late 2010, in most regions of the world, the price of wind energy with some financial aids was approximately same as that of electricity from conventional generation units such as coal, gas, or nuclear. As is demonstrated in [46] such incentives and aids should be supported by governments, additionally the cost can certainly decrease by appropriate R&D policies. In 2012 the onshore wind electricity price was stabilized around 5.6 €¢/kWh and the offshore one was approximately double of that value [49].

There are many studies which focused on feasibility assessment, economical analysis and generation costs of wind energy from different aspects like design, installation location, control systems, turbine dynamics, power system integration, and environmental impacts. They also addressed the most influential factors on costs increase or decrease and the expected future of technology [26,47,48]. While the researchers in [46] have provided a framework for the economic analysis of wind energy, an extensive review on technical and economical aspects of wind energy with respect to different input data has been carried out in [45]. They considered cost minimizing and income maximizing per kWh as the economic criteria for turbine allocation. They also proposed a method for annual wind generation cost (€¢/kWh). Different

modeling approaches and obtained results specially related to the basic economic issues corresponding to several generators produced electricity have been addressed in [44]. They reviewed and compared common production cost models and mainly focused on the role of unit commitment and economic dispatch in production cost modeling.

2.3. Wind potential

The capacity of installed wind turbines rose by 31% in 2009 and reached to 158 GW at the end of that year. World wind energy employment capacity has leaped over the last 20 years. It can be stated that installed capacity had an annual increase, about 30% during the latest decade [50,51]. However, this growth rate had a little descent in 2010 and 2011 during the global economic crisis, but referring to world energy association published report, the installed wind capacity reached 195 GW at the end of 2010. It is estimated that the integrated wind power capacity reaches to 292 GW and 425 GW at the end of 2012 and 2015 respectively [52,53].

2.4. Onshore and offshore wind

Wind farms are allocation of multiple wind turbines, which are used to convert wind power to electricity. Wind farm can cover hundreds of square kilometers with hundreds of wind turbines. Potentially onshore available wind energy is quite large, which is about 2×10^7–5×10^7 GWh in comparison with the world current total annual electricity consumption, which is about 1.5×10^7 GWh [47]. By the end of 2010, the United States owned the world′s largest onshore wind farm with maximum installed wind turbines [54]. Currently, the biggest operating wind farm is Roscoe′s wind farm in the United States with the capacity of 781.5 MW with 627 installed wind turbine and almost 400 km^2 of the undercover area [23,55]. Meanwhile, the United States is the dominating country by owning 9 out of 10 world largest farms, in near future this situation will change with the construction of wind farms, such as that of China with a capacity of 20 GW, which will be supposed to operate by the end of 2020 [56,57].

While there are many reasons for focusing on onshore wind energy, offshore wind energy proposes itself as an alternative for situations such as space scarce in installing the wind turbines [58]. Seaward wind has a couple of privileges in comparison with its onshore rival. In an offshore site, wind is available almost all the time, and commonly it is much stronger than an ordinary onshore wind exhale [59]. For these reasons larger wind farms with larger wind turbine could be established on an offshore site. Also there are some opportunities for installing noisy wind turbines with higher efficiencies, which are not employable in onshore sites [60,61]. They are located so far enough that their noise is not an important issue anymore. For instance, the noisier downwind turbines could be considered. These turbine types are more stable, have easier yawing system, provide opposing thrust and centrifugal force, and employ cheaper and softer blades. Moreover, costly tubular towers could be replaced by cheaper truss towers [61], additionally studies in [62] have signified that blades load could be reduced by using higher tip speed and decreasing the blade chord. On the other hand, there are many troublesome issues in offshore wind farms employment such as cost, maintenance and installation. Foremost the cost of construction for such a site is about twice of onshore wind farms. Maintenance of an offshore installed wind turbine is even more expensive; it costs about 5–10 times more to maintain an offshore turbine [63,64]. There are also some other challenges in offshore wind power usage such as, turbine settlement or life cycle problems which all happen if there is improper turbine implementation [65–67].

2.5. Wind turbine size

Wind turbine size becomes increasingly larger these days to capture more power and decrease generation cost of wind energy. However larger wind turbines are not necessarily better or more efficient than smaller ones [68]. A modern wind turbine generator can be about 100 times bigger than similar turbine in 1980s with eight times longer blade length [69]. While a normal wind generator was able to produce 100 kW in early and mid 1980s, their generation capacity extended to 500 kW in the early 1990s, and the development continued to reach 750 up to 1000 kW during mid-1990s. The E-115 was introduced before 2000, which was a 2.5 MW three blades wind generator with 115 m diameter. An improved version of this generator, code named as SWT-107, was launched at the end of 2004 with capacity of 3.6 MW and a blade area diameter of 107 m [31,70]. That rating is almost doubled now, and the largest installed generator is E-126, with the size of 7.5 MW [71]. However, nowadays a typical wind turbine ranges between 500 kW and 2 MW [72], but there has been plan to build V-164, a 8.0 MW wind turbine, before the end of 2015 and a 10 MW turbine afterwards [73].

3. Generators overview

By improvements in power conversion technology, different arrangements and configurations of wind energy conversion systems (WECS) have been developed and consequently, opportunities for employing various types of generators have been created [74]. Depending on the construction and operating principle of wind turbines, a classification of those which are utilizable in WECS is presented. However, there are also others, but most common wind generators could be divided into two main categories: induction generators (IGs) and synchronous generators (SGs). Both groups work using wound rotors [75].

Multi pole variable speed wound rotor synchronous generators are very commonly utilized in variable or low speed wind areas. They are lower in cost and simpler in pitch control and consequently enhance system efficiency. They also can absorb mechanical stresses and compensate the torque and power pulsation and, hence, improve power quality [18]. Squirrel cage induction generators are the other widely employed wind generators. They are specially used for hard maintenance situations or systems which require more power security because of their simplicity, reliability, and ability in limiting output power. Since normally they are not torque controlled, the outcome power includes severe fluctuations [76]. Permanent magnet synchronous generators refer to a group of generators, which uses the permanent magnets as the excitation field. Two main types of permanent magnet generators, which are commonly used as wind conversion systems, are surface mounted and inset magnets [77,78].

Most frequently used generators in wind conversion systems could be roughly categorized as follows: (1) Squirrel cage induction generators (SCIG), (2) Wound rotor induction generators (WRIG), (3) Wound rotor synchronous generators (WRSG), (4) Permanent magnet synchronous generators (PMSG), (5) DC generators, (6) Variable reluctance generators (VRG) and (7) Direct drive generators [79]. Remarkable advantages and disadvantages of each type of wind generators are briefly listed in respective subsections.

3.1. Construction

In this section, different categories of commonly used wind turbines′ generators in wind energy conversion systems are briefly presented, according to their electrical and mechanical construction.

3.1.1. Squirrel cage generators

Squirrel cage induction generators or SCIGs are utilized in different topologies. Two common usages of SCIGs are as follows [80,81]: (1)-direct connection to the main supply grid is established via a soft-starter and a transformer (Fig. 1), (2) isolated installation from main grid by a back to back AC/DC/AC convertor (Fig. 2). In direct connection condition the generator frequency is dictated by grid frequency. Consequently, rotor rotational speed is determined by generator frequency and the number of pole pairs. This method is usually used for wind generators with rated power less than 2.3 MW and the common adoptable speed variation in these systems is 1–2%, therefore, this wind conversion method is also referred as fixed speed wind conversion [82,83].

The SCIGs are also connected to network in the variable-speed mode, using power electronic convertors [81].This technology is normally employed for off-shore wind farms where HVDC is a proper method of electricity transmission. Electricity connections can be established in two different arrangements, for farm side circuit. In first application, all generators need to operate on the same speed and their outputs are paralleled using an AC bus. Then the bus voltage is converted to DC and transmitted to on-shore through a HVDC line. To exploit each wind turbine on its optimal speed, generators outputs are converted to DC by their dedicated invertors, then the resulted voltages are gathered and transferred to the on-shore site.

Typically, SCIGs network connection was established using soft starters. Thyristor soft starters are commonly used in induction wind generators for limiting inrush current and reducing mechanical stress. These ac voltage controllers usually use silicon controlled rectifiers (SCRs) for adjusting output voltage from zero up to maximum supplying voltage while damping and limiting inrush current to less than twice of the generator rated current. Consequently, they damp torque peaks and hence decrease the gear box load. Commonly, they are used for short durations corresponding to their thermal limits, and they are short circuited after a grid connection completed [80,81,84].

3.1.2. Wound rotor generators

Wound rotor wind generators have two main categories. They could be either of typical synchronous generators (Fig. 3) or induction generators (WRIG) which fell in two subcategories, dynamic slip-controlled (Fig. 4) and doubly fed induction generators (Fig. 5). Regardless of their types, these generators are normally used in variable wind speed power conversion conditions using power electronic devices together with pitch controller as mechanical speed and power controller [85].

Synchronous generators are commonly connected to the power grid through power electronic interface, as shown in Fig. 3, similar to induction generators without rotor windings, which was illustrated in Fig. 2. Normally, these electronic interfaces are large, though they can cover a wide range of wind speed variation. On the other hand, in the doubly fed induction generators′ case, stator is connected directly to the network normally through a power transformer, and a power electronic convertor is used to feed rotor winding. This gives the ability of employing smaller power electronic convertor, although it should be noted that this method usually enables the generator to adopt to wind speed variation normally in the range of 30%, however, it depends on the size of the power electronic device [86].

Dynamic slip-controlled wound rotor generators use extra power electronic controlled resistance, which is added in the rotor circuit to create a different characteristic of torque-speed. Power converter for slip controller is designed for low voltage and high-current condition. This control method provides the ability of

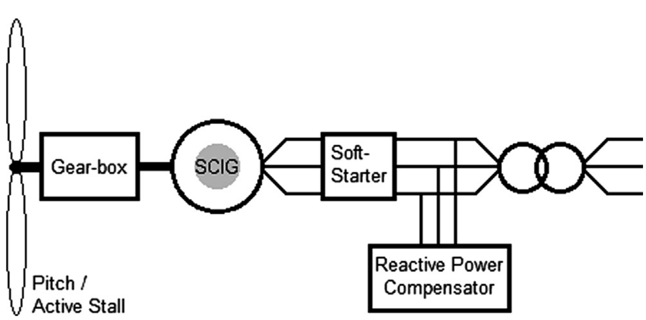


Fig. 1. Fixed speed SCIG, equipped with soft starter and reactive power compensator.

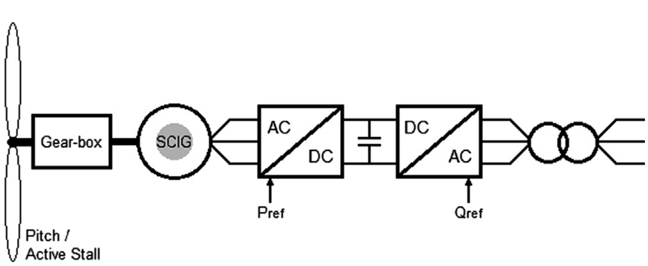


Fig. 2. Speed controlled SCIG, equipped with back to back AC/DC/AC convertors.

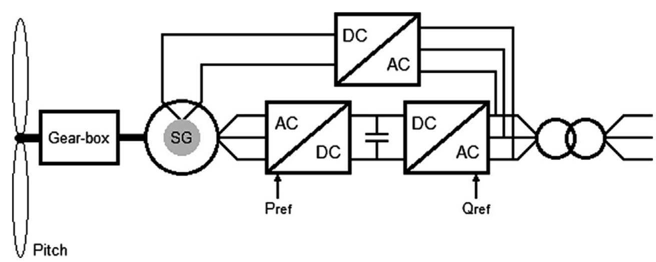


Fig. 3. Wind turbine equipped with wound rotor synchronous generator.

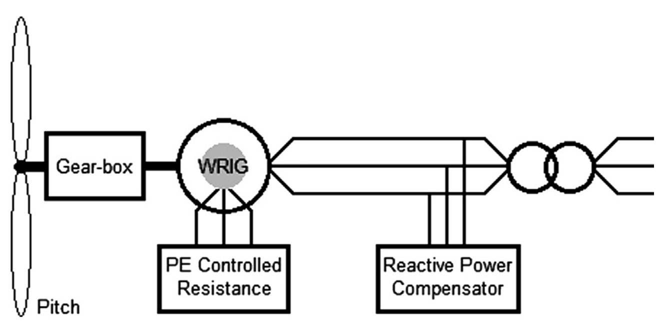


Fig. 4. Wind turbine using wound rotor induction generator with slip control circuit.

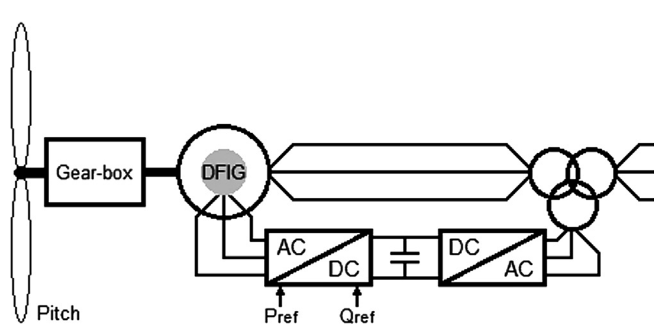


Fig. 5. Doubly fed induction generator typical installation diagram as a wind generator.

operation speed change over the range of 2–5%. These generators are normally connected directly to the ac system and needs reactive power compensator and soft starting systems [7,87].

3.1.3. Permanent magnet generators

These generators can be categorized as the most rugged system as the wind turbine generator. These generators are common for small wind turbines with a power up to 100 kW. However, they can be employed for large wind turbines as well. Normally, they are cheaper and more reliable because of rotor winding and slip ring elimination. These types of generators can be analyzed from different points of views, referring to their design and construction. Typically, they work as synchronous generators, and according to their flux they can be of three types: (1) radial flux (RFPM), (2) axial flux (AFPM), and (3) switching flux (FSPM). These generators are categorized according to their magnet installation surface mounted or inset magnets, and they can be installed either as direct drive generators or in combination with gearboxes [88–92].

3.1.4. DC generators

Shunt wound DC generators are historically highlighted type of wind electricity converters. However, these types of generators are rarely used nowadays due to their high cost and maintenance of their brushes and commutator. This type of generator was common among small wind turbines, which used to come with the battery bank. The produced power of this type was directly related to the wind speed [93,94].

3.1.5. Variable reluctance generator

Like permanent magnet generators, these special constructed generators, in spite of their common high speed uses, are most suited for the direct derive method of wind energy conversion. They have the ability to become one of the efficient methods, which are applicable in variable wind speed areas. They have some issues other than large size and diameter, which could be addressed as expensive electronic circuits dealing with their variable reluctance [95–97].

3.2. Operation

Most wind conversion systems synchronized mechanically by using a gear box before the generator and a small portion of wind conversion units directly connects wind turbine drive train to a multi-pole generator to produce a synchronous electric power.

3.2.1. Fixed speed generators

The most commonly used generators in this concept are SCIG and WRIG with slip-controlled (Figs. 1and 4). In this type of wind energy conversion, electrical output power can be controlled by several electrical and mechanical methods such as (1) Stall control, (2) Active stall control, (3) Pitch control, (4) Superconducting magnetic energy storage (SMES), (5) Static synchronous compensator (STATCOM) and (6) Braking resistor (BR); some of these methods are covered in [98,99].

The main advantage of SCIG is its simple and cheap construction. Furthermore, no synchronization device is required while it has high reliability besides its low cost. On the other hand, it had some operational drawbacks such as slow active power control by pitch controller usage (few ms response time). In addition because of direct connection, wind gusts may produce torque pulsations in drive train and gear box. Induction generators may draw high starting currents in absence of soft-starters. They also need reactive power and require strong power network for stable operation. Inrush current can be 5–7 times of the rated current or even more and such disturbances cause limitation in the number of installable induction generators in a power grid [100–104].

3.2.2. Variable speed generators

Wind turbines production technology gradually switched to variable-speed from fixed-speed by their size growth. The main motivation force for this development is the engineers′ desire to fulfill network requirements and their wish for mechanical load and stress reduction. Power electronic converters are normally used for variable-speed wind power conversion systems with pitch controller as the mechanical controller. Pitch controller is only used to limit output power and because of that the pitch is kept constant in low wind speeds to receive maximum achievable output. Researchers in [76] have carried out a comparison between fixed speed and variable speed wind turbines with respect to their (1)required hardwares, (2) operating region, and (3)energy output. According to the results of this study, in spite of fixed speed systems more simplicity and reliability, they considerably limit the wind turbine output. On the other hand, in variable speed systems even though the SCIG utilization as is shown in Fig. 2 shows improvements in power capture and reduction in mechanical stresses but WRIG (Fig. 5) brings more benefits to the wind energy conversion system. In similar rating WRIGs can significantly enhance energy harvest due to their ability of working at super-synchronous speeds. Furthermore, the size of capacitor bank, rotor side controller, and line side indicator is reduced. Generally, the following advantages may be listed for variable-speed wind conversion systems [18,105–107]:

- Reactive power compensator and soft starter system could be omitted because of power electronic devices existence.
- More power is achieved from the variable-speed generator in comparison with its constant speed counterpart system.
- Simple pitch control is available with a feasible cost.
- Mechanical stresses are reduced by absorbing and reducing torque pulsations in variable speed.
- Torque pulsation reduction improves power quality by eliminating power variation and reducing flickers.
- Maximum power point tracking systems are employable, which improve variable-speed systems efficiency.
- Acoustic noise is also reduced by working at a lower speed in lower wind gusts.

3.2.2.1. Partially rated controller. Usually this control method is applied on doubly fed induction generators (Fig. 5) and gives generators the ability to work in super or sub synchronous mode. In super-sync, both rotor and stator windings deliver power to network while in sub-sync mode, rotor absorbs power and at the same time stator produces and delivers power to network [108–111].

Speed variation range is directly dependent on the ratio of the power converter nominal power to the generator rated power. Both active and reactive power can be controlled in this scheme, and this contributes better performance of power generation, while power electronic devices give the opportunity of acting more dynamically [16,86].

3.2.2.2. Full scale controller. Full scale power converters normally consist of a back to back voltage source converter to achieve full active and reactive power control. Additionally common synchronous generator needs a small power converter to produce the field excitation (Figs. 2, 3 and 6). This control method is applicable on most of the common generators for wind power conversion such as Induction generators, Synchronous generators, Multi pole synchronous generator, and Permanent magnet multi-pole synchronous generator [75,86].

Power control and the reference values tracking with full-scale power converter may provide the fastest control method in systems in comparison to the other speed control schemes. Moreover, using the full-scale power converter brings a bunch of additional technical performances. Systems with full-scale power electronic converters wind generator are able to produce reactive power even without any wind exhale, although the active power generation is directly coupled with the available wind. However, these conversion systems could perform as a small power plan but, because of several electronic elements, these controllers are more complicated so they are more sensitive and expensive [92,112].

3.2.3. Direct drive generators

This kind of generators has lots of poles and has relatively big diameters in comparison to those which are commonly used with back to back convertors or in combination with gearboxes. They could be PMSG, WRSG or even WRIG. This type of generator could provide some flexibilities in the generator that required voltage and frequency. They also are able to decrease maintenance costs due to excitation circuit, gearbox or convertor elimination. Construction and installation cost may increase with respect to large diameter and consequently, large size of these generators [113–116].

3.3. Wind turbine starting

Wind turbines with synchronous generators are normally started by the wind and commonly active speed controllers are used for connecting energized generator to power network. Wind turbine with induction generator has two regular starting methods. In the first method wind turbine, rotor is used for speeding up generator to nominal speed and then generator is connected to the power grid. This method is usually used with pitch controlled wind turbines. However, generator speed needs to be monitored for finding synchronous speed and connection moment. From experience, this method comes with using soft stators. In the second technique, network connection is established first and induction machine is started as a motor, then wind turbine is brought to the operating speed. This method is common with stall controlled wind turbine, which can dedicate the appropriate range of wind speed for running wind turbine [26,37,117]. A schematic circuit diagram for both the methods is illustrated in Fig. 7.

4. DFIG overview

A portion of wound rotor induction generators, also known as the (DFIG), are one of the most commonly used generators in the wind energy industries [118]. Nowadays, these types of generators are widely accepted as one of the suitable wind energy conversion systems. As is depicted in Fig. 5, DFIG is naturally a wound rotor induction generator, and the rotor circuit is normally controlled by power electric devices to enable variable speed operation. DFIG stator winding typically directly connects to the grid through a power transformer while rotor winding connection is established using power convertors, harmonic filters and, finally, a transformer [103,117].

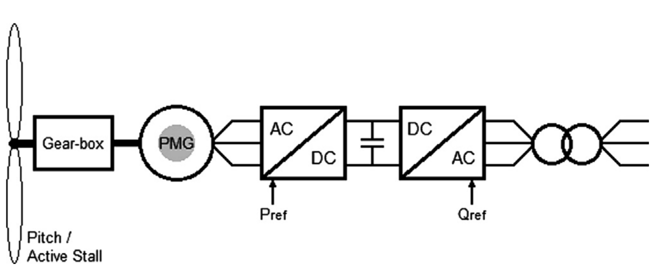


Fig. 6. Permanent magnet synchronous generator based wind turbine.

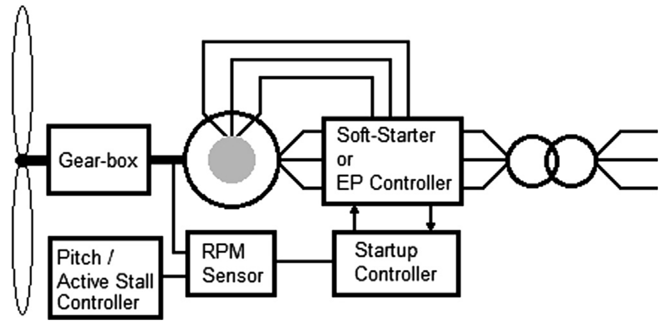


Fig. 7. Schematic diagram of wind turbines startup controller.

DFIGs′ power is generally ranged from a few kilowatts to several megawatts. In this kind of generator, power can be delivered from the stator towards the grid while the rotor is delivering or absorbing power to or from power network [76]. The size for a rotor convertor is about 30% of a full capacity convertor which is commonly installed on the stator side for a synchronous generator with the same nominal output power. Consequently, the cost of the harmonic filter and convertors for a DFIG using system are less than that of the full-scale power conversion system. Hence, during low speed wind blow more electricity could be acquired from a variable speed DFIG, in contrast with a fixed speed wind generator [119].

Smaller convertors lead to fewer power losses and result in better efficiency, while the capability of reactive power production or absorption provides the opportunity of compensation unit elimination. These characteristics have made the doubly fed induction generators the dominator of wind energy conversion system in the current energy market.

In conclusion, the benefits of using DFIG in WECS can be summarized as follows [16,18,81,117]:

- Ability of working in a wider range of wind speed.
- Improved system efficiency regarding loss reduction in smaller convertors and harmonic filters.
- Being cost efficient because of convertors and filters size.
- Capability of producing electric power more than the rated value.
- Elimination of the reactive power compensation unit.
- Having the potential of controlling power factor by an implemented unit.

4.1. Operation modes

DFIGs have two dedicated operating modes [120] as follows:

1. Operation mode, in which generator rotor rotates at a speed above the synchronous speed and is called super-synchronous. In this mode, slip is negative, and both stator and rotor windings deliver power to the grid.
2. Operation mode, in which generator operates under synchronous speed and is called as the sub-synchronous mode. In this mode, slip is positive, and stator winding delivers power to both the grid and the rotor winding. Total obtained power from stator winding does not exceed the producible power in super-synchronous mode with respect to smaller rotational speed in this mode.

4.2. DFIG utilization

There are two dedicated methods for DFIGs employment in power systems such as (1) Stand-alone installation and (2) Grid-connected usage. These two utilization methods are briefly summarized in the next two subsections.

4.2.1. Stand-alone

According to technical and economic reasons, stand-alone utilization or DFIGs isolated load supply is not an appropriate method for large power networks and consequently, not much researches are in hand in this area. However, it can be a considerably better alternative for countries with small spread islands [121]. By this way, those communities will have the opportunity of using isolated renewable and sustainable generated electricity.

While in the case of power grid, connected generators′ large loads are able to operate without much effect on network performance, stand alone DFIG systems need to be firmed and work under comprehensive control to be capable of supporting loads. This could be related to this fact that for stand-alone supplying system, there is only one supporting generator while the load combination which consumes electricity could be quite different at various times, and that will obviously affect the whole system performance.

There were some research papers that addressed the stabilizing output voltage despite variable wind speed [108], while the ability of stand-alone wind turbines in supporting unsymmetrical loads corresponding to the off-balance nature of network load was accented in [122,123]. However, some other studies intensified the harmonic elimination by different approaches [124,125], some researchers considered control methods for enhancing the performance of stand-alone generators [126,127]. Stator side voltage source convertor (VSC) is used to compensate unbalanced voltage and current of stator in [128], and authors in [129,130] concentrated on combining generators with other backup systems to make them load change tolerant.

4.2.2. Grid-connected

There are numerous papers, which have focused on doubly fed induction generators′ operation as grid-connected systems. In [131], a comparative analysis has been presented on islanded and grid-connected operation of DFIG based wind generator, where it has been utilized in combination with other reservoir and generator systems. Most of the researchers in this area are concentrated on analyzing system transients, network dynamics, grid disturbances, or fault conditions [132–138]. There are still a couple of them, which studied on reactive and active power flow control between generator and power grid [139–141]. Various control schemes for DFIGs are also discussed in different papers. A comparison control method of grid-connected DFIGs through asymmetric transmission lines has been accomplished in [142]. A non-linear decentralized control method using differential geometry theory has been applied on doubly fed induction generators [143], and the authors in [144,145] have tried to control the generator by means of current.

Since the most important problem for DFIG in the transient period is the torque pulsation, and the resulted fatigue and stress factors, some of the researchers emphasized on voltage and its dealing issues such as voltage unbalance or voltage sag [132,146–148]. Transient state analysis of a doubly fed induction generator under three phase short circuit [149], together with analysis and calculation of short circuit current of the doubly fed induction generators [150] have established the infrastructure for researchers to study on different protection methods for wind turbines [151,152]. Researchers in [153–155] have studied synchronization of DFIGs and smooth network connection for them.

By the increase in the number of wind farms which utilized DFIG, dynamic performance of this generator type during an unbalanced voltage or network condition and consequently, control of such farms, is considered by the researchers. Unbalanced network is tried to be compensated by concurrent control of grid connection and rotor convertors of a doubly fed induction generator based wind generation in [148] while in [156], rotor current is employed to control and handle DFIG-based wind farm in an unbalanced network condition. Moreover, operation and control of a series grid-side converter during a network imbalance has been discussed in [157]. Gomis-Bellmunt et al. [158] have selected current references in positive and negative sequences to ride-through unbalanced voltage sags, and preserve voltage and torque stability during the sag. Moreover, a comprehensive novel control and protection method is proposed in [159].

4.3. Modeling and simulation of DFIG

DFIG modeling and analysis return to 80s [160,161], which were intensified in steady-state analysis and characteristics [162] or performances [163] of doubly fed induction generators and tried to propose mathematical models for this kind of generators [164]. The increase in these machines′ penetration in electric networks highlighted the needs of a suitable and reliable model for these generators, which can simulate these generators′ behavior in the grid together with their responses to different occurrences in power networks [117].

While softwares such as MATLAB, DIgSILENT, PSS or PSCAD are already modeling and simulating wind turbines such as DFIGs, there are still some other favorite subjects for researchers, which need to be concerned. Two main DFIG performance categories, which have been considered by most researchers for modeling, are steady state and transient conditions. Different methods for wind turbines, especially DFIGs, network integration studies are presented in [80,82,165,166]. The researchers in [167] have concentrated on machine performance and characteristics, while cascade doubly fed induction generators modeling and control for isolated grids has been discussed in [168]. On the other hand, a couple of models have been proposed for system stability and transient analysis [169,170]. Moreover ride-through capability of doubly fed induction generators has been simulated in [132,134,171,172], while their responses in unsymmetrical voltage conditions have been focused in [133,158,173,174].

In addition, some research studies have attempted to improve the conventional proposed models by adding more complexity [175–178]. Furthermore, researchers in [179] have tried to add sliding mode control to base DFIG model or the authors in [180] and have included variable pitch parameters in the generator model. Some models′ output power controls via output feedback have been investigated by [105,181–183]. In addition, some models have been proposed and adopted for standalone generators control such as what has been illustrated by [179,184], while generators′ behavior in wind farm has been emphasized in [185–188].

5. DFIG control methods

Control of an electric grid can be the most important portion of a network operation, and this becomes more significant when it comes to DFIG based power generation, especially when speaking about wind energy conversion systems. Wind speed variation together with unpredictable consumers′ load or connections change could expose DFIG based wind power generators to a fatal stress if the system is not under an appropriate control.

A huge number of researches have been carried out to create the opportunity for building a robust and controllable power grid

with embedded DFIGs as wind power convertors [123–129,151–159,187–191]. However, most of these researches have been done under the electrical scope of control, but they could be divided into two main categories such as electrical devices and mechanical parts controllers.

5.1. Electrical

However, there are plenty of electrical control methods for DFIGs, but some of them are applicable in wind energy conversion systems. A couple of those common control methods, which are highlighted by researchers, are briefly presented in this section.

5.1.1. Vector control

Normally, vector control uses the dynamic state relationships of DFIG to determine angular speed, amplitude and instantaneous position of current, voltage and flux linkage vectors [192,193]. In contrast scalar control method proposition employs steady-state relationships to determine angular speed and amplitude of current, voltage and flux vectors [194–197]. Vector control gives the opportunity of active and reactive power control separately for generators by using d-q synchronous frame. Due to this fact, the stator flux vector is aligned with d-axis of this frame [198]. Extensive researches have been done, which show the feasibility of vector control application of DFIG for both grid-connected and stand-alone operations [108,139,199–204].

Vector control has also been used for damping inter-area oscillations in [205], by studying on active and reactive powers and their influences on damping inter-area oscillation. In [206], a DFIG power generation has been studied using computer simulation, while in [207], a vector control method has been proposed for DFIG generator which has been integrated in a hybrid wind-diesel system. In addition, a comprehensive analysis has been carried out on integrated power generation in [207]. Synchronized model of DFIG which makes it similar to a synchronous machine and thus it can be treated and controlled simpler through vector control has been presented in [208]. An equidistant field oriented vector based hysteresis current regulator (VBHCR) has been employed in [209] as the rotor side convertor (RSC).

5.1.2. Active and reactive power control

However, according to consumer demands, active power plays an important role in power networks but, from electric system behavior point of view, reactive power has an equal share as active power. An induction generator normally needs to absorb a large amount of reactive power for operation and this can significantly affect the terminal voltage [210,211]. For a grid-connected system, this reactive power can be supplied by network [212] however, a method for capacitor banks control is proposed to ease grid reconfiguration in [213].

Active and reactive power controllers for DFIGs have been represented in [140,214–216]. There are several researches that concentrated on sensorless speed identification of a variable speed DFIG [109,184,216–218], also a portion of them addressed reactive power control using sensorless vector control [108,216]. Model reference adaptive system (MRAS) is one of the most common sensorless methods, which is based on parameter estimation techniques. In [184,218–221], this method has been used as an observing system in parameter identification procedure.

5.1.3. Direct torque control

Direct torque control (DTC) proposition for induction machines returns to the mid-80 s [222,223]. It was suggested to overcome the parameters′ dependency and complexity problem of vector control method, regarding voltage source inverters′ discrete operation [224]. This method employed decoupled control of machine flux and torque hence it has the capability of direct control of linkage flux magnitude and torque of the generator [225]. DTC selects inverter switching state from a look-up table according to hysteresis controller output. In spite of DTC advantages such as an accurate and fast torque response with no rotor current regulation or complex filed oriented block, it can degrade output power quality because of current distortion and variable switching frequency caused by a hysteresis controller [192].

Some of the DTC based well known strategies are look-up table based on voltage vector selection [222], and direct self-control [223]. The main issue of basic DTC scheme deals with its starting period and operation in low speed. To solve this problem a couple of methods have been proposed such as modified switching table [196], dither signal [202], or predictive techniques [226]. The variable switching frequency problem of convertors has also been solved by means of space vector modulation [204], discrete space vector modulation [227], fuzzy logic [228], and a combination of discrete space vector modulation and fuzzy logic [229]. While in [230], output voltage vector was employed to create inverter switching duty cycles, PI controllers were selected for this purpose in [231,232], and a constant frequency DTC algorithm is studied in [233].

5.1.4. Direct power control

DTC method deals with some drawbacks such as complicated online calculation [204], additional PI controller parameters [231,232], or incapability of following machine parameter variations [204,230–232].There are some problems related to hysteresis controllers, which cause torque and current distortions and limit steady-state accuracy [192]. With respect to the principles of DTC, direct power control (DPC) was proposed for pulse width modulation (PWM) rectifiers [234–236]. In this method torque and stator active and reactive powers were implemented in control systems as feedback variables. Direct power control for DFIG-based wind turbines has been offered in [215,237–240]. However, several studies have been done on DPC methods with variable switching frequency [215,237] but, variable switching frequency results in complicated and expensive harmonic filter and power convertor. This fact led researchers to the constant frequency convertors for easier and more economic filter and convertor design [238–240].

While aforementioned schemes require complicated calculations or phase-locked loop (PLL) circuits, in [111], the power has been controlled by selecting switching vector of rotor side convertor form a lookup table. The selection has been done corresponding to the estimation error of active power, reactive power, and the position of stator flux. This goal has been achieved by the application of discrete space vector modulation (DSVM) for super-synchronous and sub-synchronous frames. Two improved DPF methods application on DFIG and grid side convertor (GSC) have been proposed in [141] to overcome the transient unbalanced grid faults′ effects. DPC application for DFIG in unbalanced network condition has also been presented in [241], and power ripples have been minimized in DPC application for DFIG by fuzzy controller and IDSVM in [242].

Since only a portion of the turbine power is being used to generate stator power, which also is employed as feedback variable in DPC controllers, the change in the speed of the turbine is dependent on the difference between turbine power and total generated power. More precisely, this difference division by the turbine speed and the moment of inertia can represent the turbine speed change. Hence, this scheme is unsuitable for generator speed control, and regarding the accuracy of speed control and the performance of maximum power point tracking (MPPT), it can be degraded. Therefore, an adaptive MPPT control strategy has been suggested in [243]. The authors in [244] have improved the

system stability and power control accuracy by using the model-based predictive DPC together with appropriate compensation methods.

5.1.5. Variable structure or sliding mode control

Usually a wind turbine works around its maximum rating in high wind speed conditions to hand out maximum achievable power. In high speed or variable wind, different oscillations influence tower, drive train, generator and even power electronic devices. In such a situation, sliding control reduces the reference value of the maximum power tracking controller to reduce the induced torque oscillations. Sliding mode control is constructed over a balance between smoothness of torque and maximum power utilization (the efficiency of conversion). Researchers in [245], suggested a static drive consisting of a diode rectifier on rotor circuit and line commuting inverter on the stator side.

There are numerous researches that have been done on the variable structure control (VSC), which is applied to the stator of the electrical drives and wind energy conversion systems [203,246–248]. The most interesting characteristic of this approach is its insensitivity to the system parameters′ variations or grid disturbances and more simplicity of implementation [246]. For solving the problem of super-synchronous mode operation, the diode rectifiers are replaced by thyristor rectifying circuit in [77,246]. Furthermore, an integral variable structure's direct torque control (IVS-DTC) of a DFIG with a space vector modulation (SVM) approach is proposed in [249]. This method is employed to eliminate power pulsation, torque pulsations, solving the parametric dependency of vector control and power quality problems of DTC and DPC methods.

A direct power control method for active and reactive power of a DFIG together with a non-linear sliding mode control has been proposed in [140], which calculates rotor control voltage to eliminate active and reactive power errors. Moreover, some other researchers have focused on using sliding mode controller dynamically for power regulation of a variable structure wind energy conversion systems (VS-WECS) by setting the output signal value to zero [250]. In addition, the sliding mode control along with the capability of zeroing system output in finite time, for a relative degree zero system, has been addressed in [251]. To overcome the problem of traditional VSC algorithm's insensitivity to system parameters variation, an integral variable structure control method in combination with a sliding mode control has been presented in [252].

5.1.6. Passivity control

Several researchers have focused on passivity-based control (PBC) for stabilizing variable speed constant frequency (VSCF) wind generators by means of energy balancing, which has resulted in an automatic power regulation for those systems. In this scheme DFIG rotor voltage has normally been taken as the control variable to control the supplying loads in [253,254]. In [255], the operating points have been defined for controller to maximize the generated power, while a non-linear model of generator has been integrated into the controller to ensure the tracking of mechanical and electrical references. Additionally two other reference speed and flux trajectory tracking methods together with a variable load torque control have been proposed in [256,257].

In [258] wind farm control scheme is employed to support the network for electromechanical oscillations damping and to stabilize the system after a disturbance. A non-linear frame inertial and droop responses are incorporated as a negative load in model formulation. By this way passivity control laws are embedded in nonlinear frame formulation, and they contribute to the stability of the system.

5.2. Mechanical

The control and limitation of mechanically converted wind power at high speed wind are important aspects of wind power generation. Therefore, appropriate controlling devices together with suitable sensors are vital for wind turbines performance enhancement and stability under variable and different environmental conditions.

5.2.1. Pitch, stall and active stall control

Wind turbine output mechanical power, beside wind speed and density, depends on blades′ radius, pitch angle and tip speed [155,259,260]. Turbine mechanical power, and consequently, its speed can be controlled by blades pitch angle. Pitch control refers to the method in which the blades are turned in the way of turbine speed reduction at higher wind speeds. In passive-stall controlled, blades positions are fixed however at high winds stall appears along the blades, while in active stall control the angles are adjusted to generate stall along the blades [81,176].

Commonly wind turbines produce mechanical power according to their power curve, which always has an optimal speed point. The goal of the pitch, passive and active stall controllers are to follow this maximum power point for different wind speeds [261,262]. In passive-stall controlled wind turbine the blades are fixed at the specific angle. The torque reaction for generator maximizes the outcome energy by limiting the rotor speed below the rated operation. Regarding the rotor design, in high wind condition the stall is being induced to limit the rotor power capture [81,176]. In pitch control the blades angle could be adjusted to exploit the wind energy more efficiently. Normally pitch angle is kept constant for low wind speeds while in high gusts, the controller tries to keep rotational speed around the maximum generation point of power curve. Furthermore, it limits output power at high wind speeds to keep produced power less than its rated value and to protect generator [263–265]. Active-stall control merges both pitch and passive-stall controls. It uses stall property of blades to perform same regulation as pitch control but, unlike pitch regulation, blades angle variation in active-stall control is small and rotates less frequently, also blades are pitched to cause stall instead of feathering [81,266].

5.2.2. Yaw control

Commonly, yaw control is employed just for reducing the yaw error (the diversity of wind turbine horizontal axis from mean wind direction) in the case of wind direction changes for maximizing exerted power [267]. This control is only used by horizontal axis wind generators (HAWG) and has become a redundant control system in the case of vertically installed wind generators. Normally, yaw system uses a delay by averaging a duration of half a minute for wind direction determination to ignore the short-period wind direction changes, especially in low speed wind areas [8]. Undoubtedly, both yaw and pitch controller systems are required for a stable and safe operation of wind turbines in variable wind conditions [35].

5.2.3. Flywheel storage

However, flywheel could be included in mechanical controller categories, but naturally it is not a dedicated control system. The main purpose of a flywheel installation is its functionality as a storage device because it can keep rotational motion of turbine much longer or more stable and smooth [78].

Flywheels′ operation has two distinct cycles: acceleration cycle which is while grid requested load is less than the generated electricity and energy delivery period that occurs when the

network demand goes beyond the provided power by turbine. Commonly, flywheels come with passive controllers, which has been discussed under electrical controllers′ [8].

In [268] a simulative study using decoupled and vector control has been done on DFIG containing flywheel energy storage. This research illustrates the impact of the flywheel on load leveling and reactive power compensation.

6. DFIG & grid mutual impacts

Power system operation is significantly affected by high penetration of wind turbines. However, in the past it did not seem to be required to take these effects into frequency and voltage calculations but, in recent years they took so much attention and number of standards (i.e. IEC 61400 parts 4, 12 and 21) have been published with main concern on this matter [81]. However, DFIGs bring lots of positive impacts for power grids; there are also obstacles, which should be overcome, on the way of wind power installation expansion. Some of these issues are overviewed in [269].

6.1. Wind exhale uncertainty

Low wind speed causes low frequency and this affects the wind energy generator output. Investigating these conditions and their effects on electricity generations has been the researchers′ favorite subject of study as well. The uncertainty of wind generated power, in case with a large number of installed wind turbines such as Belgian, and the needs for reserve capacity of conventional electricity generators during low speed wind blows have been investigated in [270]. A combination of wind estimation and nonlinear control of a DFIG-based wind turbine has been proposed for power capture optimization in [271], while the adequacy of wind potential for the supporting system frequency has been considered in [272].

6.2. Frequency and power stability

The main drawback reason, which resulted in fewer wind power harvest than the expectations, is the stability of networks with a large number of installed wind generators. A network topology independent method, using two non-linear active and reactive power control schemes for a wind farm equipped by DFIGs, has been used to damp power system electromechanical oscillations in [273]. A combination of linear and non-linear methods has been integrated to improve network stability in [274]. Results of [275] illustrate that wind power plants, with power electronic devices and the capability of low-voltage ride-through, have had the opportunity of preserving grid stability where the power network connection has been weak. Contribution of DFIGs to grid oscillation damping has been studied in [276], additionally, authors in [277] have suggested a tuned damping controller, using the bacterial techniques, to improve the DFIG-based wind power generation system stability.

A lot of research has been done to improve power stability or frequency control [87,102,189,272,278–283]. A control scheme for DFIG based wind farms, which provides the ability of voltage support, fault clearance, power system stability, and overall system damping, together with the capability of contributing to the short-term frequency, has been presented in [278]. Alemieda et al. [279] have proposed a control approach for effective participation of DFIGs in system frequency regulation. A combination of an electrical and mechanical scheme has been presented in [280] for creating the same ability. Frequency regulation through DFIG-based wind generation has also been addressed in [87,281–283].

Normal power plants with conventional power generators can provide network requested reactive power, while in the case of wind energy generators, which are equipped with doubly fed induction generators, they absorb reactive power from network for their magnetizing purposes. Hence, suitable reactive power compensator or methods are required for reduction of reactive power demand on the network. Reactive power management for DFIG based wind generators is also presented in a huge number of studies, commonly they studied on reactive power regulation together with active power [50,140,214,215], and some of them focused on the capability of doubly fed induction generators in providing reactive power [284–286]. While there are studies, which proposed new methods for reactive power compensation [213], others tried to control output voltage through the reactive power [211] or vice versa [259].

6.3. Voltage and power quality

Wind power fluctuation has a direct effect on output power quality. Large fluctuation may result in large power flicker and degradation or out of standard voltage variations. For instance, to reduce the impacts of unpredictable wind generation on stability and performance of a conventional synchronous generator or DFIG-based wind generation, a probabilistic model of wind generation using Weibull distribution for modeling the wind speed has been introduced in [110], and the results have been utilized for a damping controller design and construction. Pitch angle and torque have been controlled concurrently for optimal power and speed regulation while minimizing fluctuations of torsional torque in the drive train. Hence, WECS generated power quality and the mechanical parts of life time have been increased by employing the presented method in [180]. Another sliding mode control with the same purpose has been presented in [245].

A control scheme for controlling reactive and active power flow between a medium voltage power grid and a doubly fed induction machine has been applied on a static convertor, which was equipped with a fuzzy controller in [287]. Optimal tracking secondary voltage control (OTSVC) method has been developed for voltage control of a DFIG based wind farms in [288]. Another control strategy has been discussed in [148], for optimal reactive power compensation, and efficient voltage regulation in an interconnected power system. This scheme compensates the unbalanced voltage in AC network by employing DFIG-based wind farm. For this purpose, a complete dynamic model of DFIG including rotor and grid side convertors has been used to determine the negative sequence current for compensation.

Harmonics are one of the important parameters, which affect the power and voltage quality. In [289], researchers have focused on investigating the rotor current, voltage and torque harmonics of a variable speed constant frequency doubly output induction generator (VSCF-DOIG). Another control scheme for upgrading DFIG to a power source with the capability of reactive power support and active harmonic filtering has been presented in [290]. This method has used two approaches such as (1)- all harmonic component compensation, (2) only 5th and 7th order harmonics filtering, which both showed significant impacts on power and voltage quality. Moreover, a control method has been proposed for DFIG-based wind power generation systems which are working in a harmonically polluted network [291].

Flicker production of a wind turbine with DFIG is dependent on short circuit capacity, intensity of wind turbulence and mean wind speed. A comparison between fixed speed and variable-speed wind turbine has been accomplished to illustrate the effects of aforementioned parameters on flicker emission, in addition an effective method for flicker mitigation by means of output reactive power controller has been proposed in [292].

6.4. Steady, dynamic and fault condition operation

Steady-state analysis of a doubly fed induction generator during its synchronous operation has been done in [160], in the late 80 s. The modeling and control of DFIG-based wind turbines have also been discussed in [293]. Regarding every day growing number of DFIG-based wind generators the analysis of these generators under different operational condition is unavoidable, and consequently, there are a lot of research studies, which have focused on DFIG performance. In [294], a comparison has been carried out on power regulation of different control systems application for DFIG based wind turbines. Additionally, optimization of small wind turbine, as a battery charger, has been studied in [295].

However, a response of small signal stability in a small typical power system implies positive results in general, but from inter-area point of view, less damped signal may result in instability. The responses (e.g. electromechanical oscillations) of a wind farm which is equipped by DFIG have been inspected in [296], while small signal stability together with optimal control for a wind turbine with DFIG has been analyzed in [297]. Furthermore, the consequences of a huge number of DFIG-based wind turbines installation in power networks, on power system small signal and transients, have been investigated in [298]. An adaptive method has been proposed to enhance the dynamic performance of DFIG-base wind turbine in [299], moreover a rotor voltage control strategy has also been applied for performance improvement in [300].

It is essential to determine the effect of adding generation sources to a power grid, on the short circuit current rating of existing equipment. Plenty of studies have been carried out, which have been addressing the DFIG fault conditions [134–138,151,152,171]. Another analytical study has been performed on grid-fault response of DFIG-based wind turbine [301]. Researchers in [302] applied a symmetrical voltage sag to a DFIG and they have realized that sag effects were periodic with sag duration. The study has illustrated that the required rotor voltage for rotor current control after fault clearance was strongly influenced by the fault clearing process. The study has also concluded that the usual abrupt model of sag overestimates the sag severity, while a better and more accurate simulation of fault occurrence is achieved from discrete model of sag. The Study in [303] has focused on an energy production unit management. The authors have investigated a variable speed wind turbine (WSVT) as a main source and a super-capacitor (SC) as energy storage, which were connected to a direct current DC bus. The connection of DC bus to a balance or unbalance three-phase load was established through an inventor and an inductor and capacitor filter. The SC storage state and DC bus voltage were controlled by a buck-boost convertor and a resonant controller was utilized to reject disturbance and control the line-to-line AC voltage. It has been summarized that the power management of DC bus and the line-to-line voltage can affect the stability of three-phase voltage source under wind speed variation or load disturbance.

6.5. Protection

Huge number of installed DGs in distribution networks cause error in conventional distance and over current protections. A scheme based on effective zone protection dealing with current magnitude has been proposed in [304]. The suggested method attempted to be insensitive to the high DG penetration in a network comprising DFIG farm and PV. To avoid the DFIG control being disabled by crowbar protection on fault condition, a series dynamic resistor (SDR) based converter protection scheme has been presented in [151]. The comparison between this method and a chopper controlled braking resistor method has been illustrated in [152], while the supplementary rotor current (SRC) control has been employed for the chopper controlled braking resistor.

7. Conclusion

This paper attempts to categorize and summarize researches in wind energy extraction by the means of DFIG, especially controller systems, effects and highlighted usage points. However, DFIGs have lots of benefits, and their competitive advantages make them the favorite choice for wind energy conversion systems which can be connected to large power networks, but they are rarely used as stand-alone systems. Nevertheless, there are noticeable researches, which were carried out on small or isolated system using DFIGs but such application is rare due to control and power electronic system complexity. Although, DFIG control methods and systems have been around for so long, this area is still popular among the researchers, and advanced control schemes are still proposed as electrical or mechanical controllers. However, these methods cover both mechanical and electrical scopes; most of them may fall into the electrical categories. Even though installation characteristics such as site location, tower height or environmental parameters have great influence on DFIG electricity production, there are still a lot of networks related to installation aspects, which are considered by the researchers. The number of these network-related DFIG impacts or installation and operational concerns which were studied in the last 30 years are addressed in this overview.

Acknowledgment

This research was financially supported by Universiti Teknologi Malaysia (UTM) and the Ministry of Higher Education (MOHE), under RUG vote No. 78583.

References

[1] Sonderegger RC, Henderson D, Bubb S, Steury J. Distributed asset insight. IEEE Power and Energy Magazine 2004;2:32–9.
[2] Puttgen HB, MacGregor PR, Lambert FC. Distributed generation: semantic hype or the dawn of a new era? IEEE Power and Energy Magazine 2003;1:22–9.
[3] Rahman S. Green power: What is it and where can we find it? IEEE Power and Energy Magazine 2003;1:30–7.
[4] Martin G. Renewable energy gets the green light in chicago. IEEE Power and Energy Magazine 2003;1:34–9.
[5] Goh HH, Mohd.Zin AAB, Muda Z, Lo KL. Cost and benefits of embedded generation in power system. Institute of Engineers 2003;64:1–9.
[6] Slootweg JG, Kling WL. Is the answer blowing in the wind? IEEE Power and Energy Magazine 2003;1:26–33.
[7] Ammasaigounden N, Subbiah M. Microprocessor-based voltage controller for wind-driven induction generators. IEEE Transactions on Industrial Electronics 1990;37:531–7.
[8] Nacfaire H. Wind-diesel and wind autonomous energy systems. London: Spon Press; 1989.
[9] Hunter R, Elliot G. Wind-diesel systems: a guide to the technology and its implementation. Cambridge: Cambridge University Press; 1994.
[10] (GWEC). Global wind report. In: Council GWE, editor. Annual Market Update 2010. Brussels, Belgium; 2010.
[11] (WWEA). World wind energy report. In: Association WWE, editor. 2011. Bonn, Germany; 2011.
[12] Wiser R, Bolinger M. Wind technologies market report.National Renewable Energy Lab GCO, 2009. Berkeley: Lawrence; 68.
[13] Wu B, Lang Y, Zargari N, Kouro S. Introduction. Power conversion and control of wind energy systems. John Wiley & Sons, Inc; 1–23.
[14] Bansal RC, Bhatti TS, Kothari DP. Bibliography on the application of induction generators in nonconventional energy systems. IEEE Transactions on Energy Conversion 2003;18:433–9.
[15] Shadhu Khan PK, Chatterjee JK. Three-phase induction generators: a discussion on performance. Electric Machines & Power Systems 1999;27:813–32.
[16] Tazil M, Kumar V, Bansal RC, Kong S, Dong ZY, Freitas W, et al. Three-phase doubly fed induction generators: an overview. IET Journal on Electric Power Applications 2010;4:75–89.

[17] Bansal RC. Three-phase self-excited induction generators: an overview. IEEE Transactions on Energy Conversion 2005;20:292–9.
[18] Muller S, Deicke M, De Doncker RW. Doubly fed induction generator systems for wind turbines. IEEE Industry Applications Magazine 2002;8:26–33.
[19] Twidell J, Weir AD. Renewable energy resources. London: E & FN Spon; 2000.
[20] Self-excited GK S. induction generator research—a survey. Electric Power Systems Research 2004;69:107–14.
[21] Kishinevsky Y, Zelingher S. Coming clean with fuel cells. IEEE Power and Energy Magazine 2003;1:20–5.
[22] T-Raissi A, Block DL. Hydrogen: automotive fuel of the future. IEEE Power and Energy Magazine 2004;2:40–5.
[23] Publishing O, Agency IE. World energy outlook. Paris: Organisation for Economic Co-operation and Development; 2010; 2010.
[24] Righter RW. Wind energy in America: a history. Norman, Okla.: University of Oklahoma Press; 1996.
[25] Saidur R, Rahim NA, Islam MR, Solangi KH. Environmental impact of wind energy. Renewable and Sustainable Energy Reviews 2011;15:2423–30.
[26] Ackermann T, Söder L. An overview of wind energy-status 2002. Renewable and Sustainable Energy Reviews 2002;6:67–127.
[27] Leung DYC, Yang Y. Wind energy development and its environmental impact: a review. Renewable and Sustainable Energy Reviews 2012;16: 1031–9.
[28] Saidur R, Islam MR, Rahim NA, Solangi KH. A review on global wind energy policy. Renewable and Sustainable Energy Reviews 2010;14:1744–62.
[29] Hills RL. Power from wind: a history of windmill technology. Cambridge [England]. New York: Cambridge University Press; 1994.
[30] Price T. James blyth – britain′s first modern wind power pioneer. Wind Engineering 2005;29:191–200.
[31] Tong W. Wind power generation and wind turbine design. Southampton; Boston: WIT Press; 2010.
[32] Shepherd DG. Historical development of the windmill. ASME Press; 2009.
[33] Hau E. Wind turbines fundamentals, technologies, application, economics. Berlin; New York: Springer; 2006.
[34] Wood D. Small wind turbines analysis, design, and application. New York: Springer; 2011.
[35] Jha AR. Wind turbine technology. Hoboken: CRC Press; 2010.
[36] Landau E. The history of energy. Minneapolis: Twenty-First Century Books; 2006.
[37] Ackermann T, Söder L. Wind energy technology and current status: a review. Renewable and Sustainable Energy Reviews 2000;4:315–74.
[38] Kaldellis JK, Zafirakis D. The wind energy (r)evolution: a short review of a long history. Renewable Energy 2011;36:1887–901.
[39] Nelson V. Wind turbines. Wind energy. CRC Press; 75–99.
[40] Eldridge FR. Wind machines. Van Nostrand Reinhold Co; 1980.
[41] Le Gouriérès D. Wind power plants: theory and design. Oxford; New York: Pergamon Press; 1982.
[42] Dixon SL, Hall CA. Wind turbines. Fluid mechanics and thermodynamics of turbomachinery (6th ed.). Boston: Butterworth-Heinemann; 2010. p. 357–41 [chapter 10].
[43] Norske V, Forskningscenter R. Guidelines for design of wind turbines. Copenhagen; [Roskilde, Denmark]: Det Norske Veritas; Wind Energy Dept., Risø National Laboratory; 2002.
[44] Milligan MR. Modelling utility-scale wind power plants. Part 1: Economics. Wind Energy 1999;2:167–93.
[45] Schallenberg-Rodriguez J. A methodological review to estimate techno-economical wind energy production. Renewable and Sustainable Energy Reviews 2013;21:272–87.
[46] Krohn S, Morthorst PE, Awerbuch S. The economics of wind energy: European Wind Energy Association; 2009.
[47] Joselin Herbert GM, Iniyan S, Sreevalsan E, Rajapandian S. A review of wind energy technologies. Renewable and Sustainable Energy Reviews 2007;11:1117–45.
[48] Blanco MI. The economics of wind energy. Renewable and Sustainable Energy Reviews 2009;13:1372–82.
[49] Milborrow D. 2.15 - wind energy economics. In: Ali S, editor. Comprehensive renewable energy. Oxford: Elsevier; 2012. p. 469–501 (Editor-in-Chief).
[50] Lei S, Zengqiang M, Yang Y, Tao W, Haifeng T. Active power and reactive power regulation capacity study of DFIG wind turbine. International conference on sustainable power generation and supply, (SUPERGEN); 2009. p. 1–6.
[51] Secretariat REN. Renewables, global status report. 2011. Paris: UNEP; 2011.
[52] Harris A. Wind powers ahead. Engineering & Technology 2010;5:47–9.
[53] (IEA). Key world energy statistics. 2011. Paris; 2011. p. 82.
[54] Furkan D. The analysis on wind energy electricity eeneration status, potential and policies in the world. Renewable and Sustainable Energy Reviews 2011;15:5135–42.
[55] Wikipedia. Roscoe wind farm. Wikipedia, The Free Encyclopedia.; 2012.
[56] Haiyan L, Yanli K, Chuanglin F, Maoxun L. Wind energy resources exploitation and large-scale, non-grid-connection wind-powered industrial bases, construction in china northwest territories. World non-grid-connected wind power and energy conference, (WNWEC); 2009. p. 1–5.
[57] Wikipedia. Gansu wind farm. The Free Encyclopedia.; 2011.
[58] Lynn PA. Introduction. Onshore and offshore wind energy. John Wiley & Sons, Ltd;; 1–29.
[59] Adelaja A, McKeown C, Calnin B, Hailu Y. Assessing offshore wind potential. Energy Policy 2012;42:191–200.
[60] Daim TU, Bayraktaroglu E, Estep J, Lim DJ, Upadhyay J, Yang J. Optimizing the nw off-shore wind turbine design. Mathematical and Computer Modelling 2012;55:396–404.
[61] Breton S-P, Moe G. Status, plans and technologies for offshore wind turbines in Europe and north America. Renewable Energy 2009;34:646–54.
[62] DJHACNREL Malcolm. Windpact turbine rotor design study June 2000–June 2002. Golden, Colo: National Renewable Energy Laboratory; 2006.
[63] Levitt AC, Kempton W, Smith AP, Musial W, Firestone J. Pricing offshore wind power. Energy Policy 2011;39:6408–21.
[64] Lynn PA. Moving offshore. Onshore and offshore wind energy. John Wiley & Sons, Ltd;; 153–77.
[65] Manwell JF, Elkinton CN, Rogers AL, McGowan JG. Review of design conditions applicable to offshore wind energy systems in the united states. Renewable and Sustainable Energy Reviews 2007;11:210–34.
[66] Weinzettel J, Reenaas M, Solli C, Hertwich EG. Life cycle assessment of a floating offshore wind turbine. Renewable Energy 2009;34:742–7.
[67] Nilsson J, Bertling L. Maintenance management of wind power systems using condition monitoring systems—life cycle cost analysis for two case studies. IEEE Transactions on Energy Conversion 2007;22:223–9.
[68] Moe G. What is the optimum size for a wind turbine? ASME conference proceeding: ASME; 2007. p. 409–16.
[69] European Wind Energy A. Wind energy—the facts a guide to the technology, economics and future of wind power. Brussels, Belgium: Earthscan; 2009.
[70] Wikipedia. Wind turbine. Wikipedia, The Free Encyclopedia; 2013.
[71] European Wind Energy Association. Powering the energy debate. Annual Report 2010. Brussels, Belgium; 2011.
[72] (GWEC). Global wind energy outlook. 2010. Brussels, Belgium; 2011.
[73] European wind energy A. Upwind. Design limits and solution for very larg wind turbines. Brussels, Belgium; 2011.
[74] Boldea I. Wound rotor induction generators (wrigs). Variable speed generators. Politehnica University of Timisoara, Romania: CRC Press; 1–36.
[75] Li H, Chen Z. Overview of different wind generator systems and their comparisons. IET Journal on Renewable Power Generation 2008;2:123–38.
[76] Datta R, Ranganathan VT. Variable-speed wind power generation using doubly fed wound rotor induction machine-a comparison with alternative schemes. IEEE Transactions on Energy Conversion 2002;17:414–21.
[77] Baroudi JA, Dinavahi V, Knight AM. A review of power converter topologies for wind generators. Renewable Energy 2007;32:2369–85.
[78] Carrasco JM, Franquelo LG, Bialasiewicz JT, Galvan E, Guisado RCP, Prats MAM, et al. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Transactions on Industrial Electronics 2006;53:1002–16.
[79] Wu B, Lang Y, Zargari N, Kouro S. Wind generators and modeling. Power conversion and control of wind energy systems. John Wiley & Sons, Inc; 49–85.
[80] Quinonez-Varela G, Cruden A. Modelling and validation of a squirrel cage induction generator wind turbine during connection to the local grid. IET Journal on Generation, Transmission & Distribution 2008;2:301–9.
[81] Blaabjerg F, Chen Z. Power electronics for modern wind turbines. [San Rafael, Calif.]: Morgan & Claypool Publishers; 2006.
[82] Zhang J, Dyśko A, O′Reilly J, Leithead WE. Modelling and performance of fixed-speed induction generators in power system oscillation stability studies. Electric Power Systems Research 2008;78:1416–24.
[83] Martins M, Perdana A, Ledesma P, Agneholm E, Carlson O. Validation of fixed speed wind turbine dynamic models with measured data. Renewable Energy 2007;32:1301–16.
[84] Rahimi M, Parniani M. Dynamic behavior and transient stability analysis of fixed speed wind turbines. Renewable Energy 2009;34:2613–24.
[85] Dan L. Stand alone induction generators. Electric Power Systems Research 1997;41:191–201.
[86] Blaabjerg F, Zhe C, Kjaer SB. Power electronics as efficient interface in dispersed power generation systems. IEEE Transactions on Power Electronics 2004;19:1184–94.
[87] Anaya-Lara O, Hughes FM, Jenkins N, Strbac G. Contribution of DFIG-based wind farms to power system short-term frequency regulation. IEE proceedings on generation, transmission and distribution; 2006. Vol. 153, p. 164–70.
[88] Fuchs EF, Fardoun AA, Carlin PWErickson RW, Permanent magnet machines for operation with large speed variations. Proceedings of windpower. Seattle, Washington; 1992.
[89] Mingyao L, Li H, Xin L, Xuming Z, Zhu ZQ. A novel axial field flux-switching permanent magnet wind power generator. IEEE Transactions on Magnetics 2011;47:4457–60.
[90] Hui L, Zhe C, Polinder H. Optimization of multibrid permanent-magnet wind generator systems. IEEE Transactions on Energy Conversion 2009;24:82–92.
[91] Stegmann JA, Kamper MJ. Design aspects of double-sided rotor radial flux air-cored permanent-magnet wind generator. IEEE Transactions on Industry Applications 2011;47:767–78.
[92] Fernandez LM, Garcia CA, Jurado F. Operating capability as a pq/pv node of a direct-drive wind turbine based on a permanent magnet synchronous generator. Renewable Energy 2010;35:1308–18.
[93] Suzuki T, Okitsu H, Kawahito T. Characteristics of a small wind-power system with DC generator. IEE Proceedings on Electric Power Applications 1982;129:217–20.
[94] Guoliang Y, Huiguang L. Design and analysis of a newly brushless DC wind generator. World Automation Congress, (WAC); 2008. p. 1–5.

[95] Haan SWHd. Development of a gearless drive with variable reluctance generator for variable speed wind turbines. Petten: Netherlands Energy Research Foundation ECN; 1994.
[96] Cameron DE, Lang JH. The control of high-speed variable-reluctance generators in electric power systems. IEEE Transactions on Industry Applications 1993;29:1106–9.
[97] Hasanien HM, Muyeen SM. Speed control of grid-connected switched reluctance generator driven by variable speed wind turbine using adaptive neural network controller. Electric Power Systems Research 2012;84:206–13.
[98] Ali MH, Bin W. Comparison of stabilization methods for fixed-speed wind generator systems. IEEE Transactions on Power Delivery 2010;25:323–31.
[99] Thiringer T. Grid-friendly connecting of constant-speed wind turbines using external resistors. IEEE Transactions on Energy Conversion 2002;17:537–42.
[100] Wu B, Lang Y, Zargari N, Kouro S. Fixed-speed induction generator WECS. Power conversion and control of wind energy systems. John Wiley & Sons, Inc; 173–89.
[101] Bahramipanah M, Afsharnia S, Aslani A. A study on power system′s transient stability in determination of the appropriate generator type for wind turbines: comparison between fixed-speed induction generator equipped with energy storage system and doubly-fed induction generator. Environment and electrical engineering tenth international conference, (EEEIC); 2011. p. 1–4.
[102] Ekanayake J, Jenkins N. Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency. IEEE Transactions on Energy Conversion 2004;19:800–2.
[103] Holdsworth L, Wu XG, Ekanayake JB, Jenkins N. Comparison of fixed speed and doubly-fed induction wind turbines during power system disturbances. IEE proceedings on generation, transmission and distribution; 2003. Vol. 150, p. 343–52.
[104] Ashourian MH, Mohd Zin AA, Ferdavani AK, Mokhtar AS, Fathi M. Impact of fixed-speed wind turbine farm on radial distribution network. IEEE region 10 conference (TENCON); 2011. p. 1005–9.
[105] Hua G, Geng Y. Output power control for variable-speed variable-pitch wind generation systems. IEEE Transactions on Energy Conversion 2010;25: 494–503.
[106] Muljadi E, Pierce K, Migliore P. Soft-stall control for variable-speed stall-regulated wind turbines. Journal of Wind Engineering and Industrial Aerodynamics 2000;85:277–91.
[107] Cheng KWE, Lin JK, Bao YJ, Xue XD. Review of the wind energy generating system. Advances in Power System Control, Operation and Management 8th International Conference, (APSCOM); 2009. p. 1–7.
[108] Pena R, Clare JC, Asher GM. A doubly fed induction generator using back-to-back PWM converters supplying an isolated load from a variable speed wind turbine. IEE Proceedings on Electric Power Applications; 1996. Vol. 143, p. 380–7.
[109] Datta R, Ranganathan VT. A simple position-sensorless algorithm for rotor-side field-oriented control of wound-rotor induction machine. IEEE Transactions on Industrial Electronics 2001;48:786–93.
[110] Huang H, Chung CY. Coordinated damping control design for DFIG-based wind generation considering power output variation. IEEE Transactions on Power Systems 2012:1 (Vol:PP).
[111] Verij Kazemi M, Sadeghi Yazdankhah A, Madadi Kojabadi H. Direct power control of DFIG based on discrete space vector modulation. Renewable Energy 2010;35:1033–42.
[112] Liserre M, Ca x, rdenas R, Molinas M, Rodriguez J. Overview of multi-mw wind turbines and wind parks. IEEE Transactions on Industrial Electronics 2011;58:1081–95.
[113] Li H, Chen Z. Design optimization and site matching of direct-drive permanent magnet wind power generator systems. Renewable Energy 2009;34: 1175–84.
[114] Eriksson S, Solum A, Leijon M, Bernhoff H. Simulations and experiments on a 12 kw direct driven pm synchronous generator for wind power. Renewable Energy 2008;33:674–81.
[115] Li S, Haskew TA, Xu L. Conventional and novel control designs for direct driven PMSG wind turbines. Electric Power Systems Research 2010;80: 328–38.
[116] Fengxiang W, Rei J, Zheng W, Fengge Z. A multi-pole low speed doubly fed brushless generator for direct driven vscf wind power system. International Conference on Power System Technology, (PowerCon); 2006. p. 1–5.
[117] Wu B, Lang Y, Zargari N, Kouro S. Doubly fed induction generator based WECS. Power conversion and control of wind energy systems. John Wiley & Sons, Inc; 237–74.
[118] Smith AC, Todd R, Barnes M, Tavner PJ. Improved energy conversion for doubly fed wind generators. IEEE Transactions on Industry Applications 2006;42:1421–8.
[119] Fox B. Institution of E, Technology. Wind power integration: connection and system operational aspects. London 2007.
[120] Simões MG, Farret FA. Alternative energy systems: design and analysis with induction generators. Boca Raton; London; New York: CRC Press; 2008.
[121] Ajan CW, Ahmed SS, Ahmad HB, Taha F, Mohd Zin AAB. On the policy of photovoltaic and diesel generation mix for an off-grid site: East Malaysian perspectives. Solar Energy 2003;74:453–67.
[122] Phan VT, Lee HH. Improved predictive current control for unbalanced stand-alone doubly-fed induction generator-based wind power systems. IET Journal on Electric Power Applications 2011;5:275–87.
[123] Pena R, Cardenas R, Escobar E, Clare J, Wheeler P. Control system for unbalanced operation of stand-alone doubly fed induction generators. IEEE Transactions on Energy Conversion 2007;22:544–5.
[124] Van-Tung P, Hong-Hee L. Control strategy for harmonic elimination in stand-alone DFIG applications with nonlinear loads. IEEE Transactions on Power Electronics 2011;26:2662–75.
[125] Phan VT, Lee HH. Stationary frame control scheme for a stand-alone doubly fed induction generator system with effective harmonic voltages rejection. IET Journal on Electric Power Applications 2011;5:697–707.
[126] Van-Tung P, Hong-Hee L. Performance enhancement of stand-alone DFIG systems with control of rotor and load side converters using resonant controllers. IEEE Transactions on Industry Applications 2012;48:199–210.
[127] Forchetti DG, Solsona JA, García GO, Valla MI. A control strategy for stand-alone wound rotor induction machine. Electric Power Systems Research 2007;77:163–9.
[128] Pena R, Cardenas R, Escobar E, Clare J, Wheeler P. Control strategy for a doubly-fed induction generator feeding an unbalanced grid or stand-alone load. Electric Power Systems Research 2009;79:355–64.
[129] Vijayakumar K, Kumaresan N, Gounden NA. Operation and closed-loop control of wind-driven stand-alone doubly fed induction enerators using a single inverter-battery system. IET Journal on Electric Power Applications 2012;6:162–71.
[130] Qiao J, Lu Z, Min Y. Research on isolated diesel-wind power system equipped with doubly fed induction generator. 8th IEE International Conference AC and DC Power Transmission, (ACDC); 2006. p. 246–50.
[131] Zhou Y, Ferreira JA, Bauer P. Grid-connected and islanded operation of a hybrid power system. IEEE Power Engineering Society Conference and Exposition in Africa, PowerAfrica '07; 2007. p. 1–6.
[132] Morren J, de Haan SWH. Ridethrough of wind turbines with doubly-fed induction generator during a voltage dip. IEEE Transactions on Energy Conversion 2005;20:435–41.
[133] Seman S, Niiranen J, Arkkio A. Ride-through analysis of doubly fed induction wind-power generator under unsymmetrical network disturbance. IEEE Transactions on Power Systems 2006;21:1782–9.
[134] Hansen AD, Michalke G. Fault ride-through capability of DFIG wind turbines. Renewable Energy 2007;32:1594–610.
[135] Lihui Y, Zhao X, Ostergaard J, Zhao Yang D, Kit Po W. Advanced control strategy of DFIG wind turbines for power system fault ride through. IEEE Transactions on Power Systems 2012;27:713–22.
[136] Dawei X, Li R, Tavner PJ, Yang S. Control of a doubly fed induction generator in a wind turbine during grid fault ride-through. IEEE Transactions on Energy Conversion 2006;21:652–62.
[137] Lima FKA, Luna A, Rodriguez P, Watanabe EH, Blaabjerg F. Rotor voltage dynamics in the doubly fed induction generator during grid faults. IEEE Transactions on Power Electronics 2010;25:118–30.
[138] Kasem AH, El-Saadany EF, El-Tamaly HH, Wahab MAA. An improved fault ride-through strategy for doubly fed induction generator-based wind turbines. IET Journal on Renewable Power Generation 2008;2:201–14.
[139] Pena R, Clare JC, Asher GM. Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation. IEE Proceedings on Electric Power Applications 1996;143:231–41.
[140] Jiabing H, Heng N, Bin H, Yikang H, Zhu ZQ. Direct active and reactive power regulation of DFIG using sliding-mode control approach. IEEE Transactions on Energy Conversion 2010;25:1028–39.
[141] Zhou P, He Y, Sun D. Improved direct power control of a DFIG-based wind turbine during network unbalance. IEEE Transactions on Power Electronics 2009;24:2465–74.
[142] Dominguez Rubira S, McCulloch MD. Control method comparison of doubly fed wind generators connected to the grid by asymmetric transmission lines. IEEE Transactions on Industry Applications 2000;36:986–91.
[143] Feng W, Xiao-Ping Z, Ping J, Sterling MJH. Decentralized nonlinear control of wind turbine with doubly fed induction generator. IEEE Transactions on Power Systems 2008;23:613–21.
[144] Nisa Y, Heng N, Yu Q. A novel DC grid connected DFIG system with active power filter based on predictive current control. International Conference on Electrical Machines and Systems, (ICEMS); 2011. p. 1–5.
[145] Castilla M, Miret J, Matas J, Borrell A, Garci x, et al. Direct rotor current-mode control improves the transient response of doubly fed induction generator-based wind turbines. IEEE Transactions on Energy Conversion 2010;25:722–31.
[146] Flannery PS, Venkataramanan G. Unbalanced voltage sag ride-through of a doubly fed induction generator wind turbine with series grid-side converter. IEEE Transactions on Industry Applications 2009;45:1879–87.
[147] Yi Z, Bauer P, Ferreira JA, Pierik J. Operation of grid-connected DFIG under unbalanced grid voltage condition. IEEE Transactions on Energy Conversion 2009;24:240–6.
[148] Wang Y, Xu L, Williams BW. Compensation of network voltage unbalance using doubly fed induction generator-based wind farms. IET Journal on Renewable Power Generation 2009;3:12–22.
[149] Vicatos MS, Tegopoulos JA. Transient state analysis of a doubly-fed induction generator under three phase short circuit. IEEE Transactions on Energy Conversion 1991;6:62–8.
[150] Li DD. Analysis and calculation of short circuit current of doubly fed induction generator. IEEE/PES, Transmission and Distribution Conference and Exposition, (T&D); 2008. p. 1–4.
[151] Jin Y, Fletcher JE, O′Reilly J. A series-dynamic-resistor-based converter protection scheme for doubly-fed induction generator during various fault conditions. IEEE Transactions on Energy Conversion 2010;25:422–32.

[152] Okedu KE, Muyeen SM, Takahashi R, Tamura J. Wind farms fault ride through using DFIG with new protection scheme. IEEE Transactions on Sustainable Energy 2012;3:242–54.
[153] Tapia G, Santamaria G, Telleria M, Susperregui A. Methodology for smooth connection of doubly fed induction generators to the grid. IEEE Transactions on Energy Conversion 2009;24:959–71.
[154] Si Zhe C, Cheung NC, Yun Z, Miao Z, Xiong Min T. Improved grid synchronization control of doubly fed induction generator under unbalanced grid voltage. IEEE Transactions on Energy Conversion 2011;26:799–810.
[155] Abo-Khalil AG. Synchronization of DFIG output voltage to utility grid in wind power system. Renewable Energy 2012;44:193–8.
[156] Lie X. Enhanced control and operation of DFIG-based wind farms during network unbalance. IEEE Transactions on Energy Conversion 2008;23:1073–81.
[157] Liao Y, Li H, Yao J, Zhuang K. Operation and control of a grid-connected DFIG-based wind turbine with series grid-side converter during network unbalance. Electric Power Systems Research 2011;81:228–36.
[158] Gomis-Bellmunt O, Junyent-Ferre A, Sumper A, Bergas-Jan J. Ride-through control of a doubly fed induction generator under unbalanced voltage sags. IEEE Transactions on Energy Conversion 2008;23:1036–45.
[159] Fan L, Yin H, Miao Z. A novel control scheme for DFIG-based wind energy systems under unbalanced grid conditions. Electric Power Systems Research 2011;81:254–62.
[160] Vicatos MS, Tegopoulos JA. Steady state analysis of a doubly-fed induction generator under synchronous operation. IEEE Transactions on Energy Conversion 1989;4:495–501.
[161] Nakra HL, Dube B. Slip power recovery induction generators for large vertical axis wind turbines. IEEE Transactions on Energy Conversion 1988;3:733–7.
[162] Tamura J, Sasaki T, Ishikawa S, Hasegawa J. Analysis of the steady state characteristics of doubly fed synchronous machines. IEEE Transactions on Energy Conversion 1989;4:250–6.
[163] Salameh ZM, Kazda LF. Analysis of the steady state performance of the double output induction generator. IEEE Transactions on Energy Conversion 1986;EC-1:26–32.
[164] Brady FJ. A mathematical model for the doubly-fed wound rotor generator. IEEE Transactions on Power Apparatus and Systems 1984;PAS-103:798–802.
[165] Anita R, Babypriya B. Modelling, simulation and analysis of doubly fed induction generator for wind turbines. Journal of Electrical Engineering J Electr Eng 2009;60:79–85.
[166] Petru T, Thiringer T. Modeling of wind turbines for power system studies. IEEE Power Engineering Review 2002;22:58.
[167] Ioannides MG. Determination of frequencies in autonomous double output asynchronous generator. IEEE Transactions on Energy Conversion 1992;7:747–53.
[168] Patin N, Monmasson E, Louis JP. Modeling and control of a cascaded doubly fed induction generator dedicated to isolated grids. IEEE Transactions on Industrial Electronics 2009;56:4207–19.
[169] Ledesma P, Usaola J. Doubly fed induction generator model for transient stability analysis. IEEE Transactions on Energy Conversion 2005;20:388–97.
[170] Luna A, de Araujo Lima FK, Santos D, Rodriguez P, Watanabe EH, Arnaltes S. Simplified modeling of a DFIG for transient studies in wind power applications. IEEE Transactions on Industrial Electronics 2011;58:9–20.
[171] Ibrahim AO, Thanh Hai N, Dong-Choon L, Su-Chang K. A fault ride-through technique of DFIG wind turbine systems using dynamic voltage restorers. IEEE Transactions on Energy Conversion 2011;26:871–82.
[172] Seman S, Niiranen J, Virtanen R, Matsinen JP. Low voltage ride-through analysis of 2 mw DFIG wind turbine - grid code compliance validations. IEEE power and energy society general meeting—conversion and delivery of electrical energy in the 21st century; 2008. p. 1–6.
[173] Martinez MI, Tapia G, Susperregui A, Camblong H. DFIG power generation capability and feasibility regions under unbalanced grid voltage conditions. IEEE Transactions on Energy Conversion 2011;26:1051–62.
[174] Brekken TKA, Mohan N. Control of a doubly fed induction wind generator under unbalanced grid voltage conditions. IEEE Transactions on Energy Conversion 2007;22:129–35.
[175] Yazhou L, Mullane A, Lightbody G, Yacamini R. Modeling of the wind turbine with a doubly fed induction generator for grid integration studies. IEEE Transactions on Energy Conversion 2006;21:257–64.
[176] Slootweg JG, Polinder H, Kling WL. Representing wind turbine electrical generating systems in fundamental frequency simulations. IEEE Transactions on Energy Conversion 2003;18:516–24.
[177] Slootweg JG, de Haan SWH, Polinder H, Kling WL. General model for representing variable speed wind turbines in power system dynamics simulations. IEEE Transactions on Power Systems 2003;18:144–51.
[178] Chowdhury BH, Chellapilla S. Double-fed induction generator control for variable speed wind power generation. Electric Power Systems Research 2006;76:786–800.
[179] Junyent-Ferré A, Gomis-Bellmunt O, Sumper A, Sala M, Mata M. Modeling and control of the doubly fed induction generator wind turbine. Simulation Modelling Practice and Theory 2010;18:1365–81.
[180] Soliman M, Malik OP, Westwick DT. Multiple model multiple-input multiple-output predictive control for variable speed variable pitch wind energy conversion systems. IET Journal on Renewable Power Generation 2011;5:124–36.
[181] Uctug MY, Eskandarzadeh I, Ince H. Modelling and output power optimisation of a wind turbine driven double output induction generator. IEE Proceedings on Electric Power Applications 1994;141:33–8.
[182] Peresada S, Tilli A, Tonielli A. Power control of a doubly fed induction machine via output feedback. Control Engineering Practice 2004;12:41–57.
[183] Peresada S, Tilli A, Tonielli A. Indirect stator fux-oriented output feedback control of a doubly fed induction machine. IEEE Transactions on Control Systems Technology 2003;11:875–88.
[184] Cardenas R, Pena R, Proboste J, Asher G, Clare J. MRAS observer for sensorless control of standalone doubly fed induction generators. IEEE Transactions on Energy Conversion 2005;20:710–8.
[185] Lingling F, Kavasseri R, Zhixin Lee M, Chanxia Z. Modeling of DFIG-based wind farms for ssr analysis. IEEE Transactions on Power Delivery 2010;25:2073–82.
[186] Das MK, Chowdhury S, Chowdhury SP, Crossley PA. Doubly-fed induction generator models for optimization algorithm of wind farms. Forty-third International Universities Power Engineering Conference, (UPEC); 2008. p. 1–5.
[187] Hansen AD, Sørensen P, Iov F, Blaabjerg F. Centralised power control of wind farm with doubly fed induction generators. Renewable Energy 2006;31: 935–51.
[188] Rodríguez-Amenedo JL, Arnaltes S, Rodríguez MA. Operation and coordinated control of fixed and variable speed wind farms. Renewable Energy 2008;33:406–14.
[189] Le-Ren C-C, Wei-Ting L, Yao-Ching Y. Enhancing frequency response control by dfigs in the high wind penetrated power systems. IEEE Transactions on Power Systems 2011;26:710–8.
[190] Le-Ren C-C, Chih-Min H, Yao-Ching Y. Dynamic reserve allocation for system contingency by DFIG wind farms. IEEE Transactions on Power Systems 2008;23:729–36.
[191] Choon Yik T, Yi G, Jiang JN. Nonlinear dual-mode control of variable-speed wind turbines with doubly fed induction generators. IEEE Transactions on Control Systems Technology 2011;19:744–56.
[192] Buja GS, Kazmierkowski MP. Direct torque control of PWM inverter-fed AC motors - a survey. IEEE Transactions on Industrial Electronics 2004;51: 744–57.
[193] Quang N, Dittrich A, Thieme A. Doubly-fed induction machine as generator: control algorithms with decoupling of torque and power factor. Electrical Engineering (Archiv fur Elektrotechnik) 1997;80:325–35.
[194] Trzynadlowski AM. Scalar control methods. Control of induction motors. San Diego: Academic Press; 2001. 93–105 [chapter 5].
[195] Bose BK. Scalar decoupled control of induction motor. IEEE Transactions on Industry Applications 1984;IA-20:216–25.
[196] Vas P. Sensorless vector and direct torque control. Oxford; New York: Oxford University Press; 1998.
[197] Miller A, Muljadi E, Zinger DS. A variable speed wind turbine power control. IEEE Transactions on Energy Conversion 1997;12:181–6.
[198] Trzynadlowski AM. Dynamic model of the induction motor. Control of induction motors. San Diego: Academic Press; 2001. p. 107–117 [chapter 6].
[199] Tapia A, Tapia G, Ostolaza JX, Saenz JR. Modeling and control of a wind turbine driven doubly fed induction generator. IEEE Transactions on Energy Conversion 2003;18:194–204.
[200] Ledesma P, Usaola J. Effect of neglecting stator transients in doubly fed induction generators models. IEEE Transactions on Energy Conversion 2004;19:459–61.
[201] Huang H, Fan Y, Qiu R-C, Jiang X-D. Quasi-steady-state rotor EMF-oriented vector control of doubly fed winding induction generators for wind-energy generation. Electric Power Components and Systems 2006;34:1201–11.
[202] Kazmierkowski MP, Kasprowicz AB. Improved direct torque and flux vector control of PWM inverter-fed induction motor drives. IEEE Transactions on Industrial Electronics 1995;42:344–50.
[203] Drid S, Tadjine M, Nait-Said MS. Robust backstepping vector control for the doubly fed induction motor. IET Journal on Control Theory & Applications 2007;1:861–8.
[204] Habetler TG, Profumo F, Pastorelli M, Tolbert LM. Direct torque control of induction machines using space vector modulation. IEEE Transactions on Industry Applications 1992;28:1045–53.
[205] Zhixin M, Lingling F, Osborn D, Yuvarajan S. Control of DFIG-based wind generation to improve interarea oscillation damping. IEEE Transactions on Energy Conversion 2009;24:415–22.
[206] Li S, Haskew TA, Jackson J. Integrated power characteristic study of DFIG and its frequency converter in wind power generation. Renewable Energy 2010;35:42–51.
[207] Pena R, Cardenas R, Proboste J, Clare J, Asher G. Wind-diesel generation using doubly fed induction machines. IEEE Transactions on Energy Conversion 2008;23:202–14.
[208] Wang Z, Sun Y, Li G, Ooi BT. Magnitude and frequency control of grid-connected doubly fed induction generator based on synchronised model for wind power generation. IET Journal on Renewable Power Generation 2010;4:232–41.
[209] Mohseni M, Islam S, Masoum MAS. Using equidistant vector-based hysteresis current regulators in DFIG wind generation systems. Electric Power Systems Research 2011;81:1151–60.
[210] Li W, Shiang-Shong C, Wei-Jen L, Zhe C. Dynamic stability enhancement and power flow control of a hybrid wind and marine-current farm using smes. IEEE Transactions on Energy Conversion 2009;24:626–39.
[211] Tapia A, Tapia G, Ostolaza JX. Reactive power control of wind farms for voltage control applications. Renewable Energy 2004;29:377–92.

[212] Freitas W, Zobaa AF, Vieira JCM, McConnach JS. Issues related to wind energy conversion systems. International Journal of Energy Technology and Policy 2005;3:313–23.
[213] Diaz-Dorado E, Carrillo C, Cidras J. Control algorithm for coordinated reactive power compensation in a wind park. IEEE Transactions on Energy Conversion 2008;23:1064–72.
[214] Yamamoto M, Motoyoshi O. Active and reactive power control for doubly-fed wound rotor induction generator. IEEE Transactions on Power Electronics 1991;6:624–9.
[215] Xu L, Cartwright P. Direct active and reactive power control of DFIG for wind energy generation. IEEE Transactions on Energy Conversion 2006;21:750–8.
[216] Longya X, Wei C. Torque and reactive power control of a doubly fed induction machine by position sensorless scheme. IEEE Transactions on Industry Applications 1995;31:636–42.
[217] Hopfensperger B, Atkinson DJ, Lakin RA. Stator-flux-oriented control of a doubly-fed induction machine with and without position encoder. IEE Proceedings on Electric Power Applications 2000;147:241–50.
[218] Cardenas R, Pena R, Clare J, Asher G, Proboste J. MRAS observers for sensorless control of doubly-fed induction generators. IEEE Transactions on Power Electronics 2008;23:1075–84.
[219] Iacchetti MF. Adaptive tuning of the stator inductance in a rotor-current-based MRAS observer for sensorless doubly fed induction-machine drives. IEEE Transactions on Industrial Electronics 2011;58:4683–92.
[220] Pea R, Cerdenas R, Proboste J, Asher G, Clare J. Sensorless control of doubly-fed induction generators using a rotor-current-based MRAS observer. IEEE Transactions on Industrial Electronics 2008;55:330–9.
[221] Cardenas R, Pena R, Asher G, Clare J, Cartes J. MRAS observer for doubly fed induction machines. IEEE Transactions on Energy Conversion 2004;19:467–8.
[222] Takahashi I, Noguchi T. A new quick-response and high-efficiency control strategy of an induction motor. IEEE Transactions on Industry Applications 1986;IA-22:820–7.
[223] Depenbrock M. Direct self-control (DSC) of inverter-fed induction machine. IEEE Transactions on Power Electronics 1988;3:420–9.
[224] Arnalte S, Burgos JC, Rodríguez-Amenedo JL. Direct torque control of a doubly-fed induction generator for variable speed wind turbines. Electric Power Components and Systems 2002;30:199–216.
[225] Bonnet F, Vidal PE, Pietrzak-David M. Dual direct torque control of doubly fed induction machine. IEEE Transactions on Industrial Electronics 2007;54:2482–90.
[226] Baader U, Depenbrock M, Gierse G. Direct self control (DSC) of inverter-fed induction machine: a basis for speed control without speed measurement. IEEE Transactions on Industry Applications 1992;28:581–8.
[227] Casadei D, Serra G, Tani K. Implementation of a direct control algorithm for induction motors based on discrete space vector modulation. IEEE Transactions on Power Electronics 2000;15:769–77.
[228] Mir SA, Elbuluk ME, Zinger DS. Fuzzy implementation of direct self-control of induction machines. IEEE Transactions on Industry Applications 1994;30:729–35.
[229] Wei X, Chen D, Zhao C. Minimization of torque ripple of direct-torque controlled induction machines by improved discrete space vector modulation. Electric Power Systems Research 2004;72:103–12.
[230] Jun-Koo K, Seung-Ki S. New direct torque control of induction motor for minimum torque ripple and constant switching frequency. IEEE Transactions on Industry Applications 1999;35:1076–82.
[231] Idris NRN. Yatim AHM. Direct torque control of induction machines with constant switching frequency and reduced torque ripple. IEEE Transactions on Industrial Electronics 2004;51:758–67.
[232] Yen-Shin L, Jian-Ho C. A new approach to direct torque control of induction motor drives for constant inverter switching frequency and torque ripple reduction. IEEE Transactions on Energy Conversion 2001;16:220–7.
[233] Wong KC, Ho SL. Cheng KWE. Direct control algorithm for doubly fed induction generators in weak grids. IET Journal on Electric Power Applications 2009;3:371–80.
[234] Noguchi T, Tomiki H, Kondo S, Takahashi I. Direct power control of PWM converter without power-source voltage sensors. IEEE Transactions on Industry Applications 1998;34:473–9.
[235] Malinowski M, Kazmierkowski MP, Hansen S, Blaabjerg F, Marques G. Virtual flux based direct power control of three-phase PWM rectifiers. Conference Record of IEEE Industry Applications Conference; 2000. Vol. 4, p. 2369–75.
[236] Escobar G, Stankovic AM, Carrasco JM, Galvan E, Ortega R. Analysis and design of direct power control (dpc) for a three phase synchronous rectifier via output regulation subspaces. IEEE Transactions on Power Electronics 2003;18:823–30.
[237] Datta R, Ranganathan VT. Direct power control of grid-connected wound rotor induction machine without rotor position sensors. IEEE Transactions on Power Electronics 2001;16:390–9.
[238] Zhi D, Xu L. Direct power control of DFIG with constant switching frequency and improved transient performance. IEEE Transactions on Energy Conversion 2007;22:110–8.
[239] Abad G, Rodriguez MA, Poza J. Two-level VSC-based predictive direct power control of the doubly fed induction machine with reduced power ripple at low constant switching frequency. IEEE Transactions on Energy Conversion 2008;23:570–80.
[240] Abad G, Rodriguez MA, Poza J, Two-level VSC. based predictive direct torque control of the doubly fed induction machine with reduced torque and flux ripples at low constant switching frequency. IEEE Transactions on Power Electronics 2008;23:1050–61.
[241] Santos-Martin D, Rodriguez-Amenedo JL, Arnalte S. Direct power control applied to doubly fed induction generator under unbalanced grid voltage conditions. IEEE Transactions on Power Electronics 2008;23:2328–36.
[242] Verij Kazemi M, Moradi M, Verij Kazemi R. Minimization of powers ripple of direct power controlled DFIG by fuzzy controller and improved discrete space vector modulation. Electric Power Systems Research 2012;89:23–30.
[243] Spée R, Bhowmik S, JHR Enslin. Novel control strategies for variable-speed doubly fed wind power generation systems. Renewable Energy 1995;6:907–15.
[244] Zhi D, Xu L, Williams BW. Model-based predictive direct power control of doubly fed induction generators. IEEE Transactions on Power Electronics 2010;25:341–51.
[245] De Battista H, Puleston PF, Mantz RJ, Christiansen CF. Sliding mode control of wind energy systems with doig-power efficiency and torsional dynamics optimization. IEEE Transactions on Power Systems 2000;15:728–34.
[246] Utkin VI, Guldner J, Shi J. Sliding mode control in electro-mechanical systems. Boca Raton, FL: CRC Press; 2009.
[247] Valenciaga F, Puleston PF, Battaiotto PE. Variable structure system control design method based on a differential geometric approach: application to a wind energy conversion subsystem. IEE Proceedings on Control Theory and Applications 2004;151:6–12.
[248] Zhuang X, Rahman MF. Direct torque and flux regulation of an IPM synchronous motor drive using variable structure control approach. IEEE Transactions on Power Electronics 2007;22:2487–98.
[249] Si Zhe C, Cheung NC, Ka Chung W, Jie W. Integral sliding-mode direct torque control of doubly-fed induction generators under unbalanced grid voltage. IEEE Transactions on Energy Conversion 2010;25:356–68.
[250] De Battista H, Mantz RJ, Christiansen CF. Dynamical sliding mode power control of wind driven induction generators. IEEE Transactions on Energy Conversion 2000;15:451–7.
[251] Sira-Ramírez H. On the sliding mode control of nonlinear systems. Systems & Control Letters 1992;19:303–12.
[252] Chen SZ, Cheung NC, Wong KC, Wu J. Integral variable structure direct torque control of doubly fed induction generator. IET Journal on Renewable Power Generation 2011;5:18–25.
[253] SangCheol L, KwangHee N. Dynamic modelling and passivity-based control of an induction motor powered by doubly fed induction generator. Conference Record of the Industry Applications Conference 38th IAS Annual Meeting; 2003. Vol. 3, p. 1970–5.
[254] Becherif M, Ortega R, Mendes E, Lee S. Passivity-based control of a doubly-fed induction generator interconnected with an induction motor. Forty-second IEEE Conference on Decision and Control; 2003. Vol. 6, p. 5657–62.
[255] Monroy A, Alvarez-Icaza L. Passivity based control of a DFIG wind turbine. American control conference; 2006. p. 6.
[256] Qian P, Xu B. Passivity-based control strategies of doubly fed induction wind power generator systems. Second international conference on information science and engineering, (ICISE); 2010. p. 395–9.
[257] Xue H, Wang Y, Yang F. Adaptive passivity-based control strategies of doubly fed induction wind power generator systems. Power electronics for distributed generation systems second IEEE international symposium, (PEDG); 2010. p. 731–4.
[258] Ferna, x, ndez RD, Battaiotto PE, Mantz RJ. Wind farm control based on passivity. IEEE International Conference on Industrial Technology, (ICIT); 2010. p. 1000–5.
[259] Guo Y, Hosseini SH, Jiang JN, Tang CY, Ramakumar RG. Voltage/pitch control for maximisation and regulation of active/reactive powers in wind turbines with uncertainties. IET Journal on Renewable Power Generation 2012;6:99–109.
[260] Mirazimi SJ, Khairudin AB, Ashurian MH, Fathi M. Integration of pitch regulated fixed speed wind turbine in a radial distribution system. IEEE Symposium on Industrial Electronics and Applications, (ISIEA); 2011. p. 515–20.
[261] El Mokadem M, Courtecuisse V, Saudemont C, Robyns B, Deuse J. Fuzzy logic supervisor-based primary frequency control experiments of a variable-speed wind generator. IEEE Transactions on Power Systems 2009;24:407–17.
[262] Muljadi E, Butterfield CP. Pitch-controlled variable-speed wind turbine generation. IEEE Transactions on Industry Applications 2001;37:240–6.
[263] Wang J, Hyun Seung H. Ann based pitch angle controller for variable speed variable pitch wind turbine generation system. Sixth international forum on strategic technology, (IFOST); 2011. p. 443–7.
[264] Amendola CAM, Gonzaga DP. Fuzzy-logic control system of a variable-speed variable-pitch wind-turbine and a double-fed induction generator. Intelligent systems design and applications seventh international conference, (ISDA); 2007. p. 252–7.
[265] Wood AJ, Wollenberg BF. Power generation, operation, and control. New York, NY: Wiley; 1996.
[266] Camacho EF, Samad T, Garcia-Sanz M, Hiskens I. Control for renewable energy and smart grids. The Impact of Control Technology, Control Systems Society 2011:69–88.
[267] Fadaeinedjad R, Moallem M, Moschopoulos G. Simulation of a wind turbine with doubly fed induction generator by fast and simulink. IEEE Transactions on Energy Conversion 2008;23:690–700.
[268] Akagi H, Sato H. Control and performance of a doubly-fed induction machine intended for a flywheel energy storage system. IEEE Transactions on Power Electronics 2002;17:109–16.
[269] Bansal DRC, Zobaa DAF, Saket DRK. Some issues related to power generation using wind energy conversion systems: an overview. International Journal of Emerging Electric Power Systems 2005;3:1–17.

[270] Luickx PJ, Delarue ED, D′haeseleer WD. Impact of large amounts of wind power on the operation of an electricity generation system: Belgian case study. Renewable and Sustainable Energy Reviews 2010;14:2019–28.
[271] Boukhezzar B, Siguerdidjane H. Nonlinear control with wind estimation of a DFIG variable speed wind turbine for power capture optimization. Energy Conversion and Management 2009;50:885–92.
[272] Ping-Kwan K, Pei L, Banakar H, Boon Teck O. Kinetic energy of wind-turbine generators for system frequency support. IEEE Transactions on Power Systems 2009;24:279–87.
[273] Fernández RD, Battaiotto PE, Mantz RJ. Wind farm non-linear control for damping electromechanical oscillations of power systems. Renewable Energy 2008;33:2258–65.
[274] Fernández RD, Mantz RJ, Battaiotto PE. Linear and non-linear control of wind farms. Contribution to the grid stability. International Journal of Hydrogen Energy 2010;35:6019–24.
[275] Muljadi E, Butterfield CP, Parsons B, Ellis A. Effect of variable speed wind turbine generator on stability of a weak grid. IEEE Transactions on Energy Conversion 2007;22:29–36.
[276] Tsourakis G, Nomikos BM, Vournas CD. Contribution of doubly fed wind generators to oscillation damping. IEEE Transactions on Energy Conversion 2009;24:783–91.
[277] Mishra Y, Mishra S, Tripathy M, Senroy N, Dong ZY. Improving stability of a DFIG-based wind power system with tuned damping controller. IEEE Transactions on Energy Conversion 2009;24:650–60.
[278] Hughes FM, Anaya-Lara O, Jenkins N, Strbac G. Control of DFIG-based wind generation for power network support. IEEE Transactions on Power Systems 2005;20:1958–66.
[279] de Almeida RG, Lopes JAP. Participation of doubly fed induction wind generators in system frequency regulation. IEEE Transactions on Power Systems 2007;22:944–50.
[280] Ma HT, Chowdhury BH. Working towards frequency regulation with wind plants: combined control approaches. IET Journal on Renewable Power Generation 2010;4:308–16.
[281] Ramtharan G, Ekanayake JB, Jenkins N. Frequency support from doubly fed induction generator wind turbines. IET Journal on Renewable Power Generation 2007;1:3–9.
[282] Kayikci M, Milanovic JV. Dynamic contribution of DFIG-based wind plants to system frequency disturbances. IEEE Transactions on Power Systems 2009;24:859–67.
[283] Mauricio JM, Marano A, Gomez-Exposito A, Martinez Ramos JL. Frequency regulation contribution through variable-speed wind energy conversion systems. IEEE Transactions on Power Systems 2009;24:173–80.
[284] Santos-Martin D, Arnaltes S, Rodriguez Amenedo JL. Reactive power capability of doubly fed asynchronous generators. Electric Power Systems Research 2008;78:1837–40.
[285] Singh B, Singh SN. Reactive capability limitations of doubly-fed induction generators. Electric Power Components and Systems 2009;37:427–40.
[286] Konopinski RJ, Vijayan P, Ajjarapu V. Extended reactive capability of DFIG wind parks for enhanced system performance. IEEE Transactions on Power Systems 2009;24:1346–55.
[287] de Almeida RG, Lopes JAP, Barreiros JAL. Improving power system dynamic behavior through doubly fed induction machines controlled by static converter using fuzzy control. IEEE Transactions on Power Systems 2004;19:1942–50.
[288] Moursi ME, Joos G. Optimal tracking secondary voltage control for the DFIG wind turbines and compensator devices. Electric Power Systems Research 2009;79:1705–16.
[289] Salameh ZM, Kazda LF. Analysis of the double output induction generator using direct three-phase model. Part II: Harmonic analysis. IEEE Power Engineering Review 1987;PER-7:33–4.
[290] Gaillard A, Poure P, Saadate S, Machmoum M. Variable speed DFIG wind energy system for power generation and harmonic current mitigation. Renewable Energy 2009;34:1545–53.
[291] Nian H, Quan Y, Hu J. Improved control strategy of DFIG-based wind power generation systems connected to a harmonically polluted network. Electric Power Systems Research 2012;86:84–97.
[292] Tao S, Zhe C, Blaabjerg F. Flicker study on variable speed wind turbines with doubly fed induction generators. IEEE Transactions on Energy Conversion 2005;20:896–905.
[293] Ko H-S, Yoon G-G, Kyung N-H, Hong W-P. Modeling and control of DFIG-based variable-speed wind-turbine. Electric Power Systems Research 2008;78:1841–9.
[294] Fernandez LM, Garcia CA, Jurado F. Comparative study on the performance of control systems for doubly fed induction generator (DFIG) wind turbines operating with power regulation. Energy 2008;33:1438–52.
[295] Drouilhet S, Muljadi E, Holz R, Gevorgian V, National Renewable Energy Lab GCO, Conference: 25. annual c, et al. Optimizing small wind turbine performance in battery charging applications. United States; 1995.
[296] Tsourakis G, Nomikos BM, Vournas CD. Effect of wind parks with doubly fed asynchronous generators on small-signal stability. Electric Power Systems Research 2009;79:190–200.
[297] Wu F, Zhang XP, Godfrey K, Ju P. Small signal stability analysis and optimal control of a wind turbine with doubly fed induction generator. IET Journal on Generation, Transmission & Distribution 2007;1:751–60.
[298] Gautam D, Vittal V, Harbour T. Impact of increased penetration of DFIG-based wind turbine generators on transient and small signal stability of power systems. IEEE Transactions on Power Systems 2009;24:1426–34.
[299] Song Z, Shi T, Xia C, Chen W. A novel adaptive control scheme for dynamic performance improvement of DFIG-based wind turbines. Energy 2012;38:104–17.
[300] Rahim AHMA Habiballah IO. DFIG rotor voltage control for system dynamic performance enhancement. Electric Power Systems Research 2011;81:503–9.
[301] Pannell G, Atkinson DJ, Zahawi B. Analytical study of grid-fault response of wind turbine doubly fed induction generator. IEEE Transactions on Energy Conversion 2010;25:1081–91.
[302] Rola x, n A Co, rcoles F, Pedra J. Doubly fed induction generator subject to symmetrical voltage sags. IEEE Transactions on Energy Conversion 2011;26:1219–29.
[303] Masmoudi A, Abdelkafi A, Krichen L. Electric power generation based on variable speed wind turbine under load disturbance. Energy 2011;36:5016–26.
[304] El Halabi N, García-Gracia M, Borroy J, Villa JL. Current phase comparison pilot scheme for distributed generation networks protection. Applied Energy 2011;88:4563–9.